Improving the Detection Rate of Congenital Heart Defects: Using a Real-Time Cardiac Assessment Technique in Routine Obstetrical Screening

By

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A thesis submitted in fulfilment of the requirements for the degree, Doctor of Philosophy, Diagnostic Medical Ultrasound, Faculty of Science, Charles Sturt University 2013

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Certificate of Authorship

I hereby declare that this submission is my own work and to the best of my knowledge and belief, understand that it contains no material previously published or written by another person, nor material which to a substantial extent has been accepted for the award of any other degree or diploma at Charles Sturt University or any other educational institution, except where due acknowledgement is made in the thesis [or dissertation, as appropriate]. Any contribution made to the research by colleagues with whom I have worked at Charles Sturt University or elsewhere during my candidature is fully acknowledged.

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Name Ted Scott

Signature

Date 01/07/2014
Acknowledgements

This PhD thesis employed three research projects in order to devise a new method of screening the fetal heart during routine obstetrical sonography and translate the method to clinical practice. The first project was completed to determine the optimal imaging and assessment protocol. The second project tested the imaging and assessment protocol to determine if the method increased the detection rate of congenital heart disease compared with current methods. The third project was developed to demonstrate that the new method of screening could be translated to clinical practice using an online, master-based learning tool.

Project #1

Increasing the Detection Rate of Normal Fetal Cardiac Structures: A Real-Time Approach, Ted Scott, Hans Swan, Gerald Moran, Tapas Mondal, Judy Jones, Karm Guram, Jaime Huff, Journal of Diagnostic Medical Sonography 2008; 24; 63

This project was undertaken with the financial support of the SDMS Education Foundation, Graduate Research Award and the Bracco Diagnostics Research Award. Thanks are given to the following Sonographers: Malka Glasner, Mandie Bird, Rob Noftle and Melissa Wood for their efforts in acquiring the fetal cardiac images. Appreciation is also expressed to Philips Medical Systems Canada and Mohawk College for their support of this project. Equipment was provided by Philips Medical Systems, Canada and laboratory space was provided by Diane Barrafato associate dean, Medical Radiation Sciences, School of Health Sciences, Mohawk College.
Project #2


This project was supported by a health research grant from the Hamilton Community Foundation. This work was published as an abstract and presented orally at the American Institute of Ultrasound in Medicine 2010 Annual Convention; March 24–27, 2010; San Diego, California. Normal cases were acquired from the Department of Radiology, Grey Bruce Health Services, by Bertha Benninger, Georgia Roach, Terri Dowling, and Alicia Leudke. Abnormal cases were acquired with the help of Tapas Mondal, MD, from the Department of Pediatric Cardiology, McMaster Children’s Hospital (Hamilton, Ontario, Canada). The Fetal Heart Sonographic Assessment Tool was developed by Andrew Connery, instructional designer, Center for Teaching and Learning, Mohawk College.

Project #3

Increasing Recognition of Fetal Heart Anatomy using Online Tutorials and Mastery Learning Compared with Classroom Instructional Methods, Ted Scott, Laura Thomas, Keith Edwards, Judy Jones, Hans Swan, Andrew Wessels, *Journal of Diagnostic Medical Sonography*

The authors would like to acknowledge the efforts of University of Hawaii at Hilo Computer Sciences 460 students, Joel Cook, Jacob Shon, Kylie Gonsalves and Jermaine Vitales for their development of the “Find it First” learning application.
Verification of Authorship

I have contacted each of the co-authors relating to the publications included in this thesis to verify that I have performed the role as 1st author and I am responsible for the research concept, development and execution of each project and published paper. The verification email from each co-author is provided below with the exception of Dr. Guram who could not be located.

Dear Dr. Moran,

I would like to acknowledge your co-author role in the publication “Increasing the Detection Rate of Normal Fetal Cardiac Structures: A Real-Time Approach” as advisor to the experimental design of this study. If you accept this description of your contribution and agree that as first author, I (Ted Scott) developed the concept and should be acknowledged as the creator and 1st author of the manuscript please reply with confirmation to this email.

Best regards,

Ted

From: MORAN, GERALD (NAM RC-CA)
<gerald.moran@siemens.com>
Sent: October-21-13 2:19 PM
To: Scott, Ted
Subject: Validation of Role in "Increasing the Detection Rate of Normal Fetal Cardiac Structures: A Real-Time Approach."

Yes, Thank you Ted.

Jer
Dear Dr. Mondal,

I would like to acknowledge your co-author role in the publication “Increasing the Detection Rate of Normal Fetal Cardiac Structures: A Real-Time Approach.” as an image reviewer for this study. If you accept this description of your contribution and agree that as first author, I (Ted Scott) developed the concept and should be acknowledged as the creator and 1st author of the manuscript please reply with confirmation to this email.

Best regards,

Ted

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Sent: October-21-13 2:47 PM
To: Scott, Ted

Subject: Validation of role in "Increasing the Detection Rate of Normal Fetal Cardiac Structures: A Real-Time Approach."

Hi Ted,

I confirm that you developed the concept of this paper and should be recognized as the creator and first author for this article.

Hope this clarifies the position.

Regards

Tapas

Dear Dr. Gandehari,

I would like to acknowledge your co-author role as image reviewer in the publication, “Increasing the Detection of Congenital Heart Disease During Routine Obstetrical Screening using Two Cine-Loop Sweeps. J. Ultrasound Med., 32(6).” If you accept this description of your contribution and agree that as first author, I (Ted Scott) developed the concept and should be acknowledged as the creator and 1st author of the manuscript please reply with confirmation to this email.

Best regards,

Ted
From: Hournaz Ghandehari <hoornaz2@yahoo.com>

Sent: October-21-13 3:54 PM

To: Scott, Ted

Subject: Re; verification of role

Hi Ted,

Yes I agree.

Thanks,

Hournaz

Sent from my iPhone

Dear Dr. Thomson,

I would like to acknowledge your co-author role as image reviewer in the publication, “Increasing the Detection of Congenital Heart Disease During Routine Obstetrical Screening using Two Cine-Loop Sweeps. J. Ultrasound Med., 32(6).” If you accept this description of your contribution and agree that as first author, I (Ted Scott) developed the concept and should be acknowledged as the creator and 1st author of the manuscript please reply with confirmation to this email.

Best regards,

Ted

From: Andrea Young <ayoung107@hotmail.com>

Sent: October-21-13 3:35 PM

To: Scott, Ted

Subject: verification of role

Yes I agree.

Best wishes

Andrea Thomson

Sent from my iPhone
Dear Ms. Jozkow,

I would like to acknowledge your co-author role as image reviewer in the publication, “Increasing the Detection of Congenital Heart Disease During Routine Obstetrical Screening using Two Cine-Loop Sweeps. J. Ultrasound Med., 32(6).” If you accept this description of your contribution and agree that as first author, I (Ted Scott) developed the concept and should be acknowledged as the creator and 1st author of the manuscript please reply with confirmation to this email.

Best regards,

Ted

From: Kim Jozkow <kimjozkow@sympatico.ca>
Sent: October-21-13 4:15 PM
To: Scott, Ted
Subject: RE: verification of role - Agree

Dear Ted,

I agree with your description.

All the best,

Kim Jozkow

Dear Ms. Stromer,

I would like to acknowledge your co-author role as image reviewer in the publication, “Increasing the Detection of Congenital Heart Disease During Routine Obstetrical Screening using Two Cine-Loop Sweeps. J. Ultrasound Med., 32(6).” If you accept this description of your contribution and agree that as first author, I (Ted Scott) developed the concept and should be acknowledged as the creator and 1st author of the manuscript please reply with confirmation to this email.

Best regards,

Ted
Dear Dr. Rosta,

I would like to acknowledge your co-author role as image reviewer in the publication, “Increasing the Detection of Congenital Heart Disease During Routine Obstetrical Screening using Two Cine-Loop Sweeps. J. Ultrasound Med., 32(6).” If you accept this description of your contribution and agree that as first author, I (Ted Scott) developed the concept and should be acknowledged as the creator and 1st author of the manuscript please reply with confirmation to this email.

Best regards,

Ted

Hi Ted, Thanks for the email. I agree that you developed the concept for the publication, “Increasing the Detection of Congenital Heart Disease during Routine Obstetrical Screening using Two Cine-Loop Sweeps. J. Ultrasound Med., 32(6)” and you should be acknowledged as the creator and 1st author of the manuscript.
Best Regards, Neil Rosta

Dear Ms. Thomas,

I have described your role as a study co-ordinator for the publication, “Increasing Recognition of Fetal Heart Anatomy using Online Tutorials and Mastery Learning Compared with Classroom Instructional Methods.” submitted to the Journal of Diagnostic Medical Sonography. If you accept this description of your contribution and agree that as first author, I (Ted Scott) developed the concept and should be acknowledged as the creator and 1st author of the manuscript please reply with confirmation to this email.

Best regards,

Ted

From: Thomas, Laura
Sent: October-21-13 6:33 PM
To: Scott, Ted
Subject: Verification of role

Ted,

Yes I accept the description of study co-ordinator.

Laura Thomas

From: Scott, Ted
Sent: Monday, October 21, 2013 2:48 PM
To: mailto:jajones@rogers.com
Subject: re: Validation of role in Ted's research publications

Hi Judy,

I have described your role and contribution to the publications that have been accepted and submitted to the Journal of Diagnostic Medical Sonography and the Journal of Ultrasound in Medicine, as listed below. If you accept this description of your contribution and
agree that as first author, I (Ted Scott) developed the concept and should be acknowledged as the creator and 1st author of the manuscript please reply with confirmation to this email.


   a. Judy Jones participated as an image reviewer in this study, Ted Scott, designed the study and was the primary author of the published manuscript.


   a. Judy Jones participated as an image reviewer in this study, Ted Scott, designed the study and was the primary author of the published manuscript.


   a. Judy Jones participated as a contributor to the educational tutorials used in this study, Ted Scott, designed the study and was the primary author of the published manuscript.


   a. Judy Jones participated as editor of the manuscript, Ted Scott, was the primary author of the published manuscript.

a. Judy Jones participated as an editor of this manuscript, Ted Scott was the primary author of the published manuscript.

Best regards,

Ted

From: Judy Jones <jajones@rogers.com>
Sent: October-21-13 8:15 PM
To: Scott, Ted
Subject: Re: Validation of role in Ted's research publications

HI Ted- Yes, I agree to all.

Thanks,

Judy

On Mon, Oct 21, 2013 at 9:10 AM, Scott, Ted <ted.scott@mohawkcollege.ca> wrote:

Dear Mr. Wessels,

I have described your role as a lead software application developer for the publication, “Increasing Recognition of Fetal Heart Anatomy using Online Tutorials and Mastery Learning Compared with Classroom Instructional Methods,” submitted to the Journal of Diagnostic Medical Sonography. If you accept this description of your contribution and agree that as first author, I (Ted Scott) developed the concept and should be acknowledged as the creator and 1st author of the manuscript please reply with confirmation to this email.

Best regards,

Ted
From: Andrew W. <shixish@gmail.com>

Sent: October-21-13 9:28 PM

To: Scott, Ted

Subject: Re: re; verification of role

Yeah, that sounds great, thanks.

Dear Dr. Rosenberg,

I would like to acknowledge your co-author role as image reviewer in the publication, “Increasing the Detection of Congenital Heart Disease During Routine Obstetrical Screening using Two Cine-Loop Sweeps. J. Ultrasound Med., 32(6).” If you accept this description of your contribution and agree that as first author, I (Ted Scott) developed the concept and should be acknowledged as the creator and 1st author of the manuscript please reply with confirmation to this email.

Best regards,

Ted

From: Herschel Rosenberg <Herschel.Rosenberg@lhsc.on.ca>

Sent: October-22-13 7:36 AM

To: Scott, Ted

Subject: Re: re; verification of role

That's fine Ted.

Dr. H.C. Rosenberg MD, FRCP
Dear Dr. Edwards,

I have described your role as a software application development supervisor for the publication, "Increasing Recognition of Fetal Heart Anatomy using Online Tutorials and Mastery Learning Compared with Classroom Instructional Methods." submitted to the Journal of Diagnostic Medical Sonography. If you accept this description of your contribution and agree that as first author, I (Ted Scott) developed the concept and should be acknowledged as the creator and 1st author of the manuscript please reply with confirmation to this email.

Best regards,

Ted

From: H. Keith Edwards <hedwards@hawaii.edu>
Sent: October-22-13 1:48 AM
To: Scott, Ted
Subject: verification of study role

Hello Ted: I have no issue with you appearing as the first author.

- H. Keith Edwards

Associate Professor - Computer Science

University of Hawaii - Hilo

New Phone (2013/10/20): (808) 932-7522
Ethics Approvals

Project #1

Increasing the Detection Rate of Normal Fetal Cardiac Structures: A Real-Time Approach. Approved for research by:

Charles Sturt University, Human Research Ethics Committee, protocol number 2013/032; Mohawk College Research Ethics Board, TS 28.07.06

Project #2

Improving the Detection Rate of Congenital Heart Defects Using a Standardized, Real-Time Cardiac Assessment Technique in Routine Obstetrical Screening. Approved for research by:

Charles Sturt University, Human Research Ethics Committee, protocol number 2013/032; Mohawk College Research Ethics Board, TS 28.07.06; Hamilton Health Sciences Research Ethics Board, project #08-071; Grey Bruce Health Services, Research Ethics Board.

Project #3

The Find it First project: Improving the ability of learners to identify congenital heart disease using a simulation based assessment in an online format, compared with traditional classroom instruction. Approved for research by:

Charles Sturt University, Human Research Ethics Committee, protocol number 2013/032; McMaster University Research Ethics Board, Project # 2013-005; Mohawk College Research Ethics Board, RA 03.04.13.
Abstract

Improving the Detection Rate of Congenital Heart Defects Using a Real-Time Cardiac Assessment Technique in Routine Obstetrical Screening

Screening the fetal heart for the presence of congenital heart disease (CHD) during routine obstetrical sonography has not translated to early identification of CHD for the majority of patients (Friedberg et al., 2009; Poole et al., 2013). Limitations have been identified in the methods used to assess the fetal heart. A number of leading experts have identified the need for a real-time assessment of the fetal heart compared with the convention of relying on static images only for interpretation (Mcgahan, Moon-grady, & Pahwa, 2007; Sklansky, 2007). In addition, a deep need has been identified for education to improve the examiner’s and interpreting physician’s understanding of the sonographic features of CHD (Friedberg et al., 2009; McBrien, Sands, Craig, Dornan, & Casey, 2010).

Imaging the fetal heart is a challenging element of a routine obstetrical sonogram. The fetal heart is a very small, complex and highly dynamic structure with a normal heart rate ranging from 120-160 bpm (Fredouille, 2007). The expression of CHD varies considerably, depending on the specific congenital anomaly and the time at which the exam is performed. (Cook, Yates, & Anderson, 2004). Some severe forms of CHD including Transposition of the Great Arteries (TGA) can only be detected through visualization of the outflow tracts, while other forms such as Hypoplastic Left Heart Syndrome (HLHS) can be seen in the four chamber view (Chaoui, 2003).
Although the practice guidelines for obstetric ultrasound imaging explicitly identify the anatomic structure that should be examined during screening, considerable variation in how these structures are assessed exists (ACR Guidelines and Standards Committee, American Institute of Ultrasound in Medicine, 2003)(American Institute of Ultrasound in Medicine, 2013). The majority of screening centers rely on a few static images to demonstrate the normalcy of fetal heart including a four chamber view and both outflow tracts. Alternative approaches have been identified and these include the use of cine-loops, Doppler imaging, and three dimensional imaging, as well as detailed anatomic planes (Chaoui & Heling, 2005; Chaoui & McEwing, 2003; Mcgahan et al., 2007).

This PhD thesis includes three projects that have been completed to address potentially increasing the rate of CHD detection. The first project assessed the feasibility and efficacy of using cine-loop sweeps, grey-scale cine-loop sweeps and colour Doppler cine sweeps compared with static images only. The use of cine-loop sweeps was found to be the most effective and practical technique. The second project assessed the practicality of using cine-loop sweeps and a standardized assessment technique compared with static images only and demonstrated an increased detection rate of CHD. The third project assessed the efficacy of an online, tutorial-based tool for learning the standardized assessment technique of cine-loop sweeps used in the first two projects. Improving the detection rate of CHD during routine obstetrical sonography can be achieved with the use of a standardized
assessment of cine-loop sweeps. The translation of this technique to clinical practice can be achieved using an online learning tool.
Chapter 1 Prenatal Detection of Congenital Heart Disease

Introduction
The identification of congenital heart disease, (CHD) during the prenatal period is an important screening objective of a routine obstetrical sonogram. Despite the technological advances that have occurred within the field of diagnostic medical sonography, the detection of CHD has lagged behind the detection rates of other congenital anomalies (Grandjean, Larroque, & Levi, 1999). The opportunity for improving the detection of CHD will most likely depend on two facets of the screening process; 1) optimization of the image acquisition process and 2) the standardization of the assessment protocol. The feasibility of implementation of the optimal process and protocol will be an additional key consideration.

A thorough review of the literature was undertaken in order to fully examine the state of the art as it relates to imaging the fetal heart. This includes a review of: practice guidelines for assessment of the fetal heart, the embryological and physiological basis for CHD; the history of screening the fetal heart, the technical underpinnings of image formation in two dimensions, grey-scale mode, colour and spectral Doppler and three dimensional imaging tools. The analysis of the imaging acquisition and assessment capabilities of modern sonography systems as they relate to detecting CHD in-utero were framed by the current imaging protocols and the relative ease of implementation.
A significant limitation of current methods is the reliance on static images for assessment by the interpreting physician. Given the technical improvements in imaging systems, including image processing, Doppler and three-dimensional techniques, it may be possible to leverage these capabilities in a new image acquisition and assessment protocol.

The use of ultrasound imaging for routine fetal screening in the second trimester has been adopted by the Canadian health care system (Van den Hof & Wilson, 2005). A complete screening examination of the fetus will provide the parents and care providers with a comprehensive report of the gestational status and viability of the pregnancy. According to the American Institute of Ultrasound in Medicine (AIUM) practice guidelines, the routine screening of the fetus in the second trimester is expected to include documentation of the gestational status and fetal anatomy as defined in Table 1-1 (American Institute of Ultrasound in Medicine, 2013).
### Table 1-1

**Gestational status and anatomic structures documented in routine second trimester screening.** *(American Institute of Ultrasound in Medicine, 2013)*

<table>
<thead>
<tr>
<th>Anatomic structure</th>
<th>Imaging parameters</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gestational status</td>
<td>Fetal number, presence of cardiac activity and presentation</td>
<td>Multiple gestations require further documentation</td>
</tr>
<tr>
<td>Gestational sac</td>
<td>Placental location and assessment of amniotic fluid</td>
<td>Quantitative or semi-quantitative estimate of amniotic fluid volume should be reported</td>
</tr>
<tr>
<td>Fetal Biometry</td>
<td>Gestational age estimate, fetal weight estimate</td>
<td>Significant discrepancies between gestational age and fetal measurements may suggest fetal growth restriction or macrosomia.</td>
</tr>
<tr>
<td>Maternal adnexa</td>
<td>Uterus and adnexa</td>
<td>Allow recognition of incidental findings</td>
</tr>
<tr>
<td>Anatomic survey</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head face and neck</td>
<td>Cerebellum, choroid plexus, cisterna magna, upper lip, lateral cerebral ventricles, midline falx and cavum septum pellucidi</td>
<td></td>
</tr>
<tr>
<td>Chest</td>
<td><strong>Fetal heart, four-chamber view, Left ventricular outflow tract; and Right ventricular outflow tract</strong></td>
<td></td>
</tr>
<tr>
<td>Abdomen</td>
<td>Stomach (size, situs and presence), kidneys, bladder, umbilical cord insertion into the fetal abdomen, umbilical cord vessel number</td>
<td></td>
</tr>
<tr>
<td>Spine</td>
<td>Cervical, thoracic, lumbar and sacral spine</td>
<td></td>
</tr>
<tr>
<td>Extremities</td>
<td>Presence of legs and arms</td>
<td></td>
</tr>
<tr>
<td>Gender</td>
<td>Indicated in low-risk pregnancies only for evaluation of multiple gestations</td>
<td></td>
</tr>
</tbody>
</table>
Compared with the assessment of most fetal anatomic structures, the assessment of the fetal heart during routine screening represents a diagnostic challenge for sonographers and interpreting physicians. This is due to a number of factors; the size and complexity of the heart, screening methods used and the need for focused training to enable more effective identification of heart defects. The assessment and documentation of the fetal heart can very easily be misinterpreted as normal based on the acquisition and interpretation of static images only (Sklansky, 2007). The fetal heart is a relatively small and complex structure as seen in an early second trimester cast of a fetal heart in Figure 1-1. Key anatomical structures such as the outflow tracts are only 2-6 mm in diameter (Allan, 2004). In some forms of CHD, the abnormality may only be detectable within a relatively small fraction of the heart volume. For example, congenital heart disease relating to the outflow tracts such as dextro-transposition of the great arteries may only be detected at their origins and frequently are not detected by the four chamber view.
Figure 1-1

Cast of a fetal heart in early second trimester, obtained from the McMaster University Anatomy laboratory with the assistance of Glenn Oomen.

The normal fetal heart beat ranges from 120-160 beats per minute; each beat represents a systolic and diastolic phase equivalent to an effective unidirectional movement of 240-320 cycles per second (Pildner von Steinburg S, Boulesteix A-L, Lederer C, Grunow S, Schiemeier S, Hatzmann W, 2013). Furthermore the impact of congenital heart disease varies widely depending on the specific form it takes. In some cases the ventricles of the heart may be entirely normal in appearance and the defect may only be evidenced in the outflow tracts of the heart or in a relatively small fraction of the fetal heart volume.

Since static images of the fetal heart represent only very thin slices of the fetal heart it is very important that the fetal heart is assessed in real-time and interrogated completely in contiguous slices. The
diversity and relative complexity of congenital heart defects demands considerable skill of the sonographer and interpreting physician to ensure a complete examination.

According to a survey of 2758 referrals to the fetal cardiology unit at Guy's Hospital, London, UK, the low risk population is the source of 80% of Congenital Heart Defects (CHD) (Sharland, 2004). This underscores the importance of routine screening for detection of CHD. Routine screening provides a more accurate measure of gestational age, earlier detection of multiple pregnancies and may detect congenital malformations. The Eurofetus study identified marked differences in sensitivity for detection of different malformations, see Table 1-2.
Table 1-2

Sensitivity of routine obstetrical screening for congenital anomalies, reported in the Eurofetus study (Grandjean et al., 1999).

<table>
<thead>
<tr>
<th>Anomaly</th>
<th>Number</th>
<th>Type</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urinary tract</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Major</td>
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<td>84.8</td>
<td></td>
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<tr>
<td>Minor</td>
<td>816</td>
<td>89.1</td>
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<tr>
<td>Total</td>
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<tr>
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<tr>
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<tr>
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<tr>
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<tr>
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<td>Total</td>
<td>4615</td>
<td>Combined</td>
<td>56.2</td>
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Abnormalities of the urinary system and nervous system were most frequently detected with a sensitivity of 88.5% and 88.3% respectively (Grandjean et al., 1999). In this study cardiac abnormalities were not detected in most cases, sensitivity for major cardiac defects was 38.8% and minor defects 20.8% with a combined sensitivity of 27.7% (Grandjean et al., 1999). In Canada, the routine second trimester examination is performed in real-time and documented as a series of static images archived electronically or on film. Typically the interpretation of the cardiac images is
performed by a radiologist or obstetrician using the static images.

Present detection rates for CHD vary widely depending on a number of factors: operator skills, maternal obesity, fetal position, inadequate image optimization, image acquisition protocol and the nature of the CHD (Chaoui, 2003). In order to clarify the recommended fetal heart structures for examination the American College of Radiology (ACR), the American College of Obstetrics and Gynecology (ACOG), the Canadian Society of Gynecologists and the International Society of Ultrasound in Obstetrics & Gynecology (ISUOG) have published guidelines for routine second trimester screening (American Institute of Ultrasound in Medicine, 2013; Reddy, Abuhamad, Levine, & Saade, 2014; Van den Hof & Wilson, 2005). Both of these publications require the four chamber view, also known as a basic assessment and where possible views of the left ventricular outflow tract (LVOT) and right ventricular outflow tracts (RVOT) commonly referred to as an extended examination (ACR Guidelines and Standards Committee, American Institute of Ultrasound in Medicine, 2003; Lee et al., 2008).

Development of the Fetal Heart
Heart Tube Formation
The first organ to develop during embryogenesis is the fetal heart; it completes development by the end of the first trimester (Lohr, Martin, & Garry, 2012). The process of gastrulation describes molecular signalling activities that result in the fusion of the anterior and lateral mesoderm to form the heart tube in the midline of the embryo. This single tube begins to beat at 22-23 days gestation and Doppler
imaging can demonstrate blood flow between four to five weeks gestation (Lohr, Martin, & Garry, 2012). During the fourth and fifth weeks of gestation, the epicardial cells arise from the proepicardium and migrate over the heart tube to contribute to the connective tissue of the myocardium and epicardium defining the coronary arteries (Abdulla, Blew, & Holterman, 2004).

**Formation of the Vascular System**

The vascular system forms at the same time as the fetal heart. The arterial and venous systems form bilaterally and they are symmetric initially, anterior aortic arches, posterior and anterior cardinal veins are paired. The paired dorsal aorta fuse into a single thoraco-abdominal aorta early in embryogenesis, while the dual aortic arches and paired venous return persist until six to eight weeks gestation (Moore & Persaud, 2008).

![Diagram](image)

**Figure 1-2**

The heart tube is anchored at both ends. As the tube grows, it bends on itself to the right, the green circle represents the future right ventricle, the red square represents the future left ventricle. Illustrations prepared by Ken Wong Graphic Designer, Mohawk College.
**Cardiac Looping**

Elongation of the heart tube between 22-28 days gestation generates the primitive outflow and inflow tracts. Rightward looping brings the inflow region to a cranial position, this looping process establishes the anatomic relationships needed for normal chamber formation and septation. See Figure 1-2. Severe forms of congenital heart disease and outflow tract defects are associated with disturbances in the looping process such as, Transposition of the Great Arteries (TGA). (Kirby & Waldo, 2002).

**Chamber Formation and Septation**

Septation begins at the same time as looping and the elongated heart tube narrows to form the conotruncus (outflow tracts), ventricular chambers, atrioventricular sulcus, primitive atrial chamber and the sinus venosus. At the atrioventricular sulcus the myocardium forms the endocardial cushion during the fifth week of gestation. The endocardial cushion divides the heart into left and right chambers (Abdulla et al., 2004). The atrial and ventricular septa fuse with the endocardial cushion to complete the septation of the cardiac chambers. The septum primum is a thin membrane which divides the atria and fuses during the fifth week of gestation. This septum develops an opening, the foramen secondum which provides access for shunting of blood during gestation from the right to left side of the heart. A thicker and more muscular septum secundum overlaps the septum primum creating a flap like valve over the foramen ovale. The ventricular septum also develops during this period, a muscular septum grows through proliferation and trabeculation of the ventricles.
while the inlet, membranous and outflow septa close with the fusion of the bulbar ridges and the endocardial cushion fusing with the muscular septum (Lohr, Martin, & Garry, 2012). The most common form of congenital heart disease results from a failure of the septum to close completely which results in an interventricular septal defect (Hoffman & Kaplan, 2002).

**Cardiac Outflow Tract Formation and Innervation**

Parasympathetic innervation and septation of the outflow tracts in the developing heart is governed by the cardiac neural crest (CNC) cells. These cells migrate from the neural tube and have a unique molecular signature. CNCs also contribute to the development of the anterior parasympathetic plexus (Kirby & Waldo, 2002).

**Formation of the Valves and Conduction System**

The cardiac valves are formed at the atrioventricular canal and outflow tracts, originating from the endocardial cushion. They are fully developed by the tenth week of gestation. Structurally, the valves are comprised of fibrous tissue which stretches and becomes thin during development. Initially the myocardium generates cardiac impulses, while the specialized conduction system develops during the fifth week of gestation. The sinus and av nodes form and as the chambers form and undergo septation, the bundle of HIS and purkinje fibers are developed (Lohr, Martin, & Garry, 2012). The fetal heart is completely formed and functional by the end of the first trimester, although the sarcomeres continue to undergo significant changes in metabolism and growth following birth (Cook et al., 2004).
Fetal Cardiac Anatomy and Physiology
The fetal cardiovascular system is structurally and physiologically
different than the mature, postnatal cardiovascular system. The
presence of three vascular shunts, the ductus venosus, the foramen
ovale and the ductus arteriosus define a parallel circulation that relies
on the maternal placenta for gas exchange and metabolic needs.
The fetal heart pumps blood to the placenta through the right
ventricle, main pulmonary artery and the ductus arteriosus as well as
the left ventricle directly into the aorta. The right ventricle is dominant
and accounts for between 60-65% of the combined cardiac output.
(Cohen, 2001) During this time the pulmonary circulation is in
development and not yet functional. Pulmonary circulation is
characterized by a high degree of flow resistance in utero, and low
flow volume. The nature of a parallel circulation is to favour a low
resistance path and therefore only a small fraction of the fetal blood
supply passes through the left and right pulmonary arteries to the
lungs.

Deoxygenated blood returns to the placenta through the internal iliac
arteries into the umbilical cord and back to the placenta. Within the
capillary network of the placenta the returning fetal blood is
oxygenated and enriched with nutrients. The oxygen saturation of
85% returning from the placenta is less than that of the 100%
saturation of blood later in post natal life (Cohen, 2001; Kiserud &
Acharya, 2004). The relatively low saturation level is offset by a
higher percentage of hemoglobin in the fetal blood. Fetal blood flow
returns to the fetus by the umbilical vein and into the fetal cord
insertion entering the body through the abdominal wall becoming the ductus venosus where it goes on to join the left portal vein in the liver. The ductus venosus shunts approximately 30% of the blood into the heart at mid-gestation with the remainder perfusing the liver (Kiserud & Acharya, 2004). Mixing of oxygenated and deoxygenated blood in the right atrium occurs as systemic venous blood returns through the Superior Vena Cava (SVC) and the Inferior Vena Cava (IVC) adding to the oxygenated blood provided by the placenta through the ductus venosus. The architecture of the flow path into the atrium favours a flow of oxygenated blood from the ductus venosus across the right atrium and into the left atrium through the foramen ovale with minimal mixing of oxygenated and deoxygenated blood. This ensures that the fetal brain and myocardium receives blood flow with a higher oxygen concentration relative to the blood flow mixed with a higher concentration of systemic venous return provided to the rest of the body through the ductus arteriosus and descending aorta (Limperopoulos et al., 2010). At birth the ductus arteriosus and foramen ovale shunts will close completely within 48 hours while the ductus venosus and umbilical vein will close completely within one-three weeks (Kiserud & Acharya, 2004).
Figure 1-3

A para-sagittal plane illustrates in blue Doppler coding, blood flow in the Ductus Venosus, see arrow, panel A. A wide arrow points to the descending aorta, visualized in panel B. A transverse plane of shunting blood flow from the right atrium into the left atrium across the foramen ovale is depicted in blue Doppler coding, see arrow, in panel C. The blue Doppler coding at the arrow defines the shunting of blood through the ductus arteriosus in a para-sagittal place in panel C. The relationship between the ductal arch and the aortic arch is defined in panel D.

Images A, B and C, provided by Nick Arbic, Hospital for Sick Children, Toronto Ontario. Image D, Ken Wong Graphic Designer, Mohawk College

Exclusive of the shunting provided by the ductus arteriosus and foramen ovale previously described in Figure 1-3, the fetal heart can be defined by three sets of connections on each side of the heart in
alignment to function. The venous, atrioventricular and ventriculoarterial connections are described as follows;

1. Right side of the heart, systemic venous blood returns to the right atrium from the SVC and IVC while on the left side of the heart, four pulmonary veins return blood from the lungs to the left atrium.

2. The tricuspid valve provides a connection between the right atrium and the right ventricle and the mitral valve creates an opening between the left atrium and the left ventricle.

3. A pulmonary valve connects the right ventricle with the pulmonary circulation and on the left side, the aortic valve joins the left ventricle with the aorta.

The superior vena cava and inferior vena cava can be visualized sonographically. The superior vena cava is best visualized in the three vessel view along with the main pulmonary artery and ascending aorta, see Figure 1-4. The pulmonary venous connections can be frequently seen entering the left atrium in real-time see Figure 1-5. In a pilot study, Scott et al identified the pulmonary veins entering the left atrium using cine-loop sweeps in 56% of cases compared to only 3.6% of static images (Scott et al., 2008).
Figure 1-4

The superior vena cava, the ascending aorta and the main pulmonary artery. Image provided by Nick Arbic, Hospital for Sick Children, Toronto Ontario. Illustrations by Ken Wong, Graphic Designer, Mohawk College.

Figure 1-5

The pulmonary veins, indicated by the red arrow heads in A can be seen entering the left atrium in a posterior view of the fetal heart. Pulmonary veins are visible and identified by red arrowheads entering the left atrium in B.

Image A provided by, Ken Wong, Graphic Designer, Mohawk College
The right ventricle is separated from the right atrium by the tricuspid valve, comprised of inferior, septal and anteriorsuperior leaflets. During the closure of the atrioventricular canal and creation of right and left inlets, the right atrium drapes over the ventricular septum. This has the effect of displacing the tricuspid valve towards the apex relative to the mitral valve (Cook et al., 2004). The offset of the tricuspid valve represents an important criterion of normal structure since, a number of forms of CHD, including AVSD and Ebstein’s anomaly will not share this feature. The surface of the right ventricle is trabeculated and leaves a coarse appearance relative to the left ventricle which is smooth walled. The moderator band is a prominent muscle that traverses the apex of the right ventricle further differentiating the right ventricle from the left ventricle. Both ventricles are normally equal in size. The outlet of the right ventricle is separated by a muscular structure known as the crista supraventricularis or conus and this forms the subpulmonary infundibulum as seen in Figure 1-6. The infundibulum is a tube of muscle that supports the leaflets of the pulmonary valve and runs obliquely right-left in an infero-superior direction over the aortic root and valve towards the pulmonary trunk as seen in Figure 1.6. The routing of the right ventricular outflow tract along this path results in a vitally important relationship, the cross-over relative to the left ventricular outflow tract at an angle of approximately 70 degrees. A number of forms of congenital heart disease broadly characterized as conotruncal defects will disturb this anatomical arrangement, see Figure 1-8.
Figure 1-6

In A, the anterior wall of the right ventricle has been removed and the right ventricular inflow and outflow tracts are visualized adjacent to the aorta. The region between the yellow shaded region defines the RVOT. An image representing the RVOT sonographically is seen in B.

Image A provided by, Ken Wong, Graphic Designer, Mohawk College

The left ventricle compared with the right ventricle is smooth walled with the shape of a ballerina’s foot where the mitral valve represents the back of the heel, the toes the apex and the aorta the leg, see Figure 1-7 (Cook et al., 2004). The left ventricular outflow
tract and aortic valve is directed at an angle relative to the right ventricular outflow tract passing posterior to the left ventricular outflow tract and pulmonary valve.

Figure 1-7

In A, a section exposes the left ventricle and outflow tract. The yellow circle denotes the interventricular septum. Double arrow defines the left ventricle and the region approaching the LVOT. The corresponding sonogram is seen in B.
Figure 1-8

The blue arrows indicate blood flow out of the right ventricle while the red arrows describe flow leaving the left ventricle. The parallel configuration of the outflow tracts associated with the transposition spectrum of CHD is defined.

Images A provided by Judy Jones, London Health Sciences. Image B provided by Ken Wong, Graphic Designer, Mohawk College.

Causes of Congenital Heart Disease and Prevention

There have been major developments in the understanding of inherited causes of CHD over the last 15 years. In parallel, a growing body of evidence has been accumulating to identify non-inherited modifiable factors that may adversely affect the fetal heart (Jenkins et al., 2007). The heart is one of the most deeply examined organs and one of the most prone to disease (Srivastava, 2006). Historically, the occurrence of most CHD in populations has been attributed to isolated cases of disease with no known causes identifiable. Studies of recurrence and transmission risks have led to the proposal of a unifying hypothesis that a multifactorial etiology
exists (Pierpont et al., 2007). In this form of inheritance, genetic predisposition of the individual combined with subsequent environmental interactions result in disruptions that influence the patterning and morphogenesis of the fetal heart (Meyer-Wittkopf, 2002). While the proportion of cases of CHD that can be prevented by modifications to the fetal environment are unknown, a study by Wilson et al. suggests that the fraction attributable to identifiable and modifiable factors may be as high as 30% for some types of CHD (Wilson, 1998). A summary of linkages established between specific forms of CHD and various environmental exposures by Jenkins et al is described in Table 1-3 (Jenkins et al., 2007). Note that the analysis of the exposure risk compares the likelihood of exposure versus non-exposure as a ratio by defect. The exposure period includes three months prior to pregnancy and the first trimester of pregnancy.
### Table 1-3

Congenital defect and associated exposures by risk ratio (Jenkins et al., 2007).

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<th>Exposure</th>
<th>Risk Ratio</th>
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</thead>
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<td>Pregestational diabetes</td>
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<tr>
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<td>Febrile illness</td>
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<td></td>
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<td>1.86</td>
</tr>
<tr>
<td></td>
<td>Sulfasalazine</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td>Thalidomide</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Trimethoprim-Sulfonamide</td>
<td>2.1-4.8</td>
</tr>
<tr>
<td></td>
<td>Vitamin A congeners/retinoids</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Organic solvents</td>
<td>2.3-3.9</td>
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<tr>
<td>Conotruncal</td>
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<tr>
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<tr>
<td></td>
<td>Febrile illness</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>Influenza</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
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</tr>
<tr>
<td></td>
<td>Epilepsy</td>
<td>*</td>
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<td>1.9</td>
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<td>2.1-4.9</td>
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<td></td>
<td>Vitamin A congeners/retinoids</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Organic solvents</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Marijuana</td>
<td>1.9</td>
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<tr>
<td>Ventricular septal defect</td>
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<td></td>
<td>Ibuprofen</td>
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<tr>
<td></td>
<td>Organic solvents (with intact ventricular septum)</td>
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<tr>
<td>D-TGA</td>
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<tr>
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<tr>
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<td>1.8-2.9</td>
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<tr>
<td></td>
<td>Influenza</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>Maternal rubella</td>
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<tr>
<td></td>
<td>Epilepsy</td>
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</tr>
<tr>
<td></td>
<td>Anticonvulsants</td>
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<td></td>
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<tr>
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<td>Trimethoprim-Sulfonamide</td>
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<tr>
<td>Ebstein’s anomaly</td>
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<td></td>
<td>Marijuana</td>
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<td></td>
<td>Organic solvents</td>
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<td></td>
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<td></td>
<td>Maternal rubella</td>
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<td></td>
<td>Sulfasalazine</td>
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<tr>
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<tr>
<td></td>
<td>Trimethoprim-Sulfonamide</td>
<td>2.1-4.8</td>
</tr>
<tr>
<td></td>
<td>Vitamin A congeners/retinoids</td>
<td>*</td>
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</tbody>
</table>
The management of maternal conditions including pre-gestational diabetes, Phenylketonuria, epilepsy, febrile illness and a variety of infections including, rubella and influenza is an important dimension of prenatal healthcare. In particular, uncontrolled pre-gestational diabetes and untreated phenylketonuria present relatively high risk conditions for the development of congenital heart disease. Fortunately both of these conditions can be treated or controlled. Early identification of pre-gestational diabetes is very important to ensure successful management since most malformations due to diabetes will occur before the seventh week of gestation (Jenkins et al., 2007).

In addition to the maternal exposure to the conditions described in Table 1-3, the risk of developing congenital heart disease can be extended to include two additional categories, familial and fetal. Familial risks include: previous child with CHD, paternal CHD, Mendelian syndromes (tuberous sclerosis, noonan syndrome, and DiGeorge /velocardiofacial syndrome (Small & Copel, 2004). Fetal extracardiac anomalies including, omphalacele, duodenal atresia, spina bifida, VACTERAL, trisomies, DiGeorge/velocardiofacial syndrome, increased NT measurement, nonimmune hydrops, arrhythmias, abnormal four chamber view, and abnormal cardiac axis (Small & Copel, 2004). All of the risk factors defined above as maternal, fetal, and familial indicate follow-up with comprehensive fetal echocardiography.

During routine second trimester screening, eight sonographic, soft markers should be evaluated, five of which:
1. Thickened nuchal fold
2. Echogenic bowel
3. Mild ventriculomegaly
4. Choroid plexus cyst
5. Echogenic focus in the heart


Echogenic IntraCardiac Focus (EICF) is defined as a focus of echogenicity comparable to fetal bone in the region of the papillary muscle in either or both ventricles of the fetal heart, however it is primarily seen in the left ventricle (Alfred Z. Abuhamad, 2010; Van den Hof & Wilson, 2005). The guidelines for diagnosing EICF were defined by Winn et al. and include four criteria in order to avoid false positive identification and include the following:

1. Located within the ventricle at the papillary muscle
2. Visible from multiple angles
3. Visible from non-specular incidence

EICF is not associated with congenital heart disease (Van den Hof & Wilson, 2005; Winn et al., 2003). Society of Obstetricians and
Gynecologists of Canada practice guidelines recommend that assessment of the fetal heart for EICF be included in all sonograms performed between 16-20 weeks. For those women with an isolated EICF and a risk of fetal aneuploidy of greater than 1/600 by maternal age or maternal serum screening, should be offered counselling regarding fetal karyotyping.

Up to 33% of CHD are associated with fetal aneuploidy (Wimalasundera & Gardiner, 2004). Wimalasundera et al., found that aneuploidy conditions were linked to CHD as follows:

- Trisomy 21 and Trisomy 18 are most closely linked to AVSD, VSD, Tetralogy of Fallot, DORV and Coarctation of the aorta.
- Trisomy 18 is also linked to HLHS
- Trisomy 21 is most closely linked to Coarctation, HLHS and DORV
- 22q11 deletion, linked to, interrupted aortic arch type b, VSD, Tetralogy of Fallot and Truncus Arteriosus (Wimalasundera & Gardiner, 2004).

Nuchal translucency (NT) is defined as the sonolucent region seen in the posterior aspect of the fetus during the first trimester (Hyett, 2004). An increased thickness of this tissue may be associated with chromosomal abnormality. It is possible to measure this thickness and apply thresholds above which chromosomal abnormalities can be detected. It has proven to be particularly effective for screening trisomy 21 (Snijders et al., 1998). See Figure 1-9. The fetal nuchal translucency measurement is made in a sagittal section with a
magnification such that the fetus occupies at least 75% of the image and the maximum thickness of the subcutaneous translucency between the skin and soft tissue overlying the spine is measured (Snijders et al., 1998). Early evidence describes an association between increased NT and major cardiac defects in fetuses with NT greater than 2.5 mm and is similar to the increased risk associated with maternal diabetes or family history of CHD (Hyett, 2004). A study led by Westin et al, explored the possibility that NT evaluation could be useful as a screening method for isolated CHD. In their examination of 16,383 fetuses measuring the NT, 127 cases with a diagnosis of CHD; 52 of these were confirmed as isolated with a sensitivity of only 13.5% (Westin et al., 2006). The poor performance of NT in identifying CHD suggests that it is not a viable alternative to sonographic screening.

**Figure 1-9**

Red arrows represent the ideal location for measuring the nuchal translucency. Illustration prepared by Ken Wong Graphic Designer, Mohawk College.
Two strategies have been suggested to reduce the burden of CHD on populations. The first and preferred strategy is primary prevention (Botto & Correa, 2003). Primary prevention is a means of identifying causes and removing or avoiding exposures to known causes in order to reduce the incidence of the disease within the population. A number of conditions and teratogens including, maternal diabetes, Phenylketonuria and anticonvulsants have been summarized in Table 1-3 that are amenable to post-operative care following early and accurate diagnostic ultrasound imaging, therapy or avoidance. The use of vitamin supplements may support prevention. Jenkins et al have reported several trials that demonstrate significant risk reduction through the use of multivitamins containing folic acid (Jenkins et al., 2007). The second strategy is an attempt to mitigate the impact of those affected by CHD. This involves complex clinical care and execution of leading edge surgical practices and post-operative care.

History of Screening for Congenital Heart Disease
The first reported use of sonographic technology to assess the fetal heart in North America was described by Winsberg at McGill University in Montreal, Canada (Winsberg, 1972). Winsberg applied a real-time B-scanning technique and m-Mode imaging to derive estimates of left ventricular output in 13 fetuses and 11 neonates. His early work along with others, (Lange et al., 1980) provided some evidence that sonographic techniques might contribute to the diagnostic assessment and management of the fetal heart. Early work documenting congenital heart disease advanced in the 1980s,
In the eighties, the focus was on high risk pregnancies and the four chamber view was the primary plane of assessment. In the late eighties and early nineties, colour and pulsed Doppler were applied to the examination in order to assess the functional status of the fetal heart and better appreciate the pathophysiology of congenital heart disease (Hornberger, 2008). In the nineties, major improvements in computer processing power along with innovations in transducer design translated into a variety of powerful beam formation and image processing capabilities. Modern ultrasound imaging systems are capable of vastly superior contrast and spatial resolution compared with the systems available in the seventies and eighties. Image quality improvements based on broad bandwidth signal processing has provided improved contrast resolution using, tissue harmonic signal processing, spatial and frequency compounding, and adaptive filters. Transducer design and construction also contributed to improvements in spatial resolution and contrast resolution. Many of the digital image processing and transducer design innovations of the nineties have provided the technical requirements to generate three-dimensional images in real-time. These innovations resulted in significant improvements in spatial resolution, volume manipulation and assessment. Image quality improvements in the nineties made the attainment of high quality diagnostic images much more accessible to sonographers and interpreting physicians. As the millennium approached, two distinct approaches to three-dimensional imaging
of the fetal heart became available to examiners and interpreting physicians. The Spatial-Temporal Image Correlation (STIC) technology, demonstrated a three-dimensional view of the fetal heart based on the acquisition of image data integrated over time, typically five to ten seconds of real-time data (Devore, Falkensammer, Sklansky, & Platt, 2003). A real-time, three dimensional imaging technology also became available which is called four dimensional imaging. This approach acquired three-dimensional data in real-time using a matrix of transducers (Stetten & Tamburo, 2001).

Similarly enhancements during this period in Digital Imaging and Communications in Medicine (DICOM) and computer networks have enabled imaging facilities to store vast amounts of image data in a fully integrated electronic medical record. The first decade of this century has seen a maturation of these technical innovations and a significant consolidation of equipment manufacturers in the global marketplace. Despite these technical advances, improvements commensurate with the new capabilities provided by sonographic imaging systems failed to translate to a significant rise in the detection rate of congenital heart disease (Friedman, Kleinman, & Copel, 2002). Recent trends in equipment product development have shifted towards design of hand held devices to serve the growing use of the technology by non-experts including, emergency physicians, anesthetists, sports medicine physicians and related professionals.
The application of sonographic imaging technology to the fetal heart has matured from an adjunct clinical tool into a field of its own, with pediatric cardiology, at the intersection of perinatology and pediatric cardiology (Hornberger, 2008). The prenatal diagnosis of congenital heart disease is critically important for a number of reasons;

1. To allow early access to high risk clinical expertise
2. To determine specific preparations for delivery
3. To assuage parental expectations
4. To allow the patient termination considerations
5. To ease parental anxiety when confirming normality.

Prevalence and Classification of Congenital Heart Disease
In an early, large prospective study, Mitchell, Korones & Berenedes (1971) defined a congenital heart defect as a, “gross structural abnormality of the heart or intrathoracic great vessels that is actually or potentially of functional significance” (Mitchell, Korones, & Berendes, 1971). Abnormalities of systemic veins and arteries along with, arrhythmias unassociated with structural malformations are also excluded. A patent ductus arteriosus is considered normal for the first 14 days of the neonatal period. Congenital heart disease can also be defined by the potential impact on fetal viability and practical implications for survival. A critical CHD is one that requires invasive intervention within the first month of life (Gazit, Huddleston, Checchia, Fehr, & Pezzella, 2010).

Typically, the incidence of disease is defined by the number of newly affected individuals expressed as a unit of time or per
population. Within the context of congenital heart disease this is usually defined by thousands or millions of live births in a year. The prevalence is defined as the difference between those born and living with the disease and those who have died (Hoffman & Kaplan, 2002). Estimating the incidence of CHD to a high degree of accuracy is quite challenging since some mild forms will go undetected and more severe forms may die early after birth and not be diagnosed via autopsy (Hoffman & Kaplan, 2002). Incidence is usually estimated based on one of two approaches: 1) large numbers of live births recording the number of those born with CHD and 2) smaller numbers of live births usually from a single regional centre. In the first case, recording all of the cases of CHD is unlikely to occur leading to a potential for underestimation. In the second case, smaller numbers within the sample may be inadequate to accurately represent the true incidence of congenital heart disease within the population (Hoffman & Kaplan, 2002). According to a systematic review by van der Linde et al, globally the prevalence of CHD has increased over time from 0.6 per 1000 live births in 1930-1934 to 9.1 per 1000 live births after 1995 (van der Linde et al., 2011). Prevalence in Europe was significantly higher, 8.2 per 1000 live births compared with 6.9 per 1000 live births in North America (van der Linde et al., 2011). The distribution of congenital heart disease can be defined as severe for those that will require expert care, moderate for those that will require care, and mild for those that may resolve spontaneously. Based on the analysis of 44 studies, Hoffman et al have determined that the incidence of
severe CHD is stable at 2.5-3 per 1000 live births, moderately severe accounting for another 3 per 1000 live births and 13 per 1000 live births will have bicuspid aortic valves that may eventually need care (Hoffman & Kaplan, 2002). Severe forms of CHD that can be further defined as cyanotic and acyanotic. Cyanotic forms are those that result in hypoxia at birth usually due to an intact interventricular septum. Acyanotic defects are those where left to right mixing of oxygenated blood and deoxygenated blood is possible either through the atrial or ventricular septum or a patent ductus arteriosus. Common severe and mild forms of CHD are listed in Table 1-4.
Table 1-4  
Sonographic Features of Severe Congenital Heart Disease (Cook et al., 2004).

<table>
<thead>
<tr>
<th>Anomaly by classification</th>
<th>Sonographic Feature(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Severe-cyanotic</strong></td>
<td></td>
</tr>
<tr>
<td>D-TGA</td>
<td>Parallel outflow tracts</td>
</tr>
<tr>
<td>Tetralogy of Fallot</td>
<td>Overriding aorta, large membranous VSD and the pulmonary artery is smaller than the aorta</td>
</tr>
<tr>
<td>HLHS</td>
<td>The left ventricle is small relative to the right ventricle</td>
</tr>
<tr>
<td>- Aortic atresia</td>
<td>Hypertrophy of LV, non contractile or poorly contracting LV</td>
</tr>
<tr>
<td>- Mitral atresia</td>
<td></td>
</tr>
<tr>
<td>HRHS</td>
<td>The right ventricle is small relative to the left ventricle</td>
</tr>
<tr>
<td>- Ebsteins anomaly</td>
<td>Apical displacement of the Tricuspid valve</td>
</tr>
<tr>
<td>- Pulmonary atresia and intact Ventricular septum</td>
<td>Pulmonary valve is replaced by a non opening membrane of tissue</td>
</tr>
<tr>
<td>- Tricuspid atresia</td>
<td>Tricuspid valve is replaced by a non opening band of tissue</td>
</tr>
<tr>
<td>Single Ventricle</td>
<td>Single ventricle – one large ventricle, second ventricle may be present but extremely small</td>
</tr>
<tr>
<td>DORV</td>
<td>Parallel outflow tracts, emerging from the RV, often with some override</td>
</tr>
<tr>
<td>Truncus Arteriosus</td>
<td>Single outflow tract overriding both ventricles</td>
</tr>
<tr>
<td>TAPVR</td>
<td>Small left atrium and often left ventriclepulmonary veins not visualized entering the LA</td>
</tr>
<tr>
<td>Pulmonary stenosis (critical)</td>
<td>Valve thickening and RV hypertrophy</td>
</tr>
<tr>
<td><strong>Severe-acyanotic</strong></td>
<td>Large defect of the Inlet septum and absent interatrial septum, single Atrioventricular valve spanning across the septal defects</td>
</tr>
<tr>
<td>AVSD (complete)</td>
<td>Large defect in the ventricular septum</td>
</tr>
<tr>
<td>Ventricular septal defect (large)</td>
<td></td>
</tr>
<tr>
<td>Aortic Stenosis (critical)</td>
<td>Thickening of the valve, LV may hypertrophy, then dilate and become poorly contractile</td>
</tr>
<tr>
<td>Pulmonary stenosis (severe)</td>
<td>Thickening of the valve, may include hypertrophy of the RV.</td>
</tr>
<tr>
<td>Coarctation (critical)</td>
<td>Narrowing of aorta, usually distal to the left subclavian artery</td>
</tr>
<tr>
<td><strong>Mild</strong></td>
<td>Small defect in the ventricular septum</td>
</tr>
<tr>
<td>Ventricular septal defect (small)</td>
<td>Mild thickening of the leaflets</td>
</tr>
<tr>
<td>Pulmonary stenosis (mild)</td>
<td>Two cusps form the aortic valve often leading to stenosis</td>
</tr>
<tr>
<td>Bicuspid Aortic Valve (BAV)</td>
<td></td>
</tr>
</tbody>
</table>
The transposition of the great arteries is one of the most common forms of CHD occurring in 2.5-5% of all cases (Gazit et al., 2010). TGA with an intact ventricular septum represents about 75% of these cases and results in parallel and separated circulatory paths between the pulmonary and systemic circulatory systems. In the absence of significant mixing at the level of the ductus arteriosus and atrial septum the potential for severe cyanosis is very high. The four chamber view in the majority of these cases, will appear normal. Detection of TGA is usually made on the basis of visualizing the outflow tracts in parallel rather than in their characteristic crossing over orientation. This form of CHD has been found to be frequently missed in prenatal screening (Yeo et al., 2011). Yates et al, using data provided by the British Paediatric Cardiac Association found that less than 20% of these are identified with prenatal screening (Yates, 2004). This finding is in agreement with a study by Jaeggi comparing the pattern, management and outcome of pre-versus post natally diagnosed major CHD. In this study, on average only 6.5% of CHD that require visualization of the outflow tracts were detected before birth (Jaeggi, Sholler, Jones, & Cooper, 2001).
Figure 1-10

The sonogram displays a Tetralogy of Fallot which is evident in the sonogram above as an abnormal cardiac axis and ventricular septal defect. In the adjacent line drawing, the narrowing of the pulmonary artery, the overriding aorta, right ventricular hypertrophy and ventricular septal defect are depicted. Line drawings provided by Ken K. Wong, Graphic Designer, Mohawk College.

Tetralogy of Fallot is the most common form of cyanotic CHD representing 3-5% of all infants born with CHD (Apitz, Webb, & Redington, 2009). TF is defined as: 1) right ventricular outflow obstruction; 2) right ventricular hypertrophy; 3) over-riding aorta and; 4) ventricular septal defect (VSD). It was first attributed to Canadian, Maude Abbott in 1924 (Apitz et al., 2009). Identification of a ventricular septal defect and over-riding aorta are key sonographic features, see Figure 1-10. In addition the pulmonary artery is usually smaller than the aorta. Inclusion of outflow tract views, in addition to the four chamber view, greatly enhances the likelihood of prenatal detection.
Figure 1-11

In this image the asymmetry in the chamber size is defined in the four-chamber view. This is an example of Hypoplastic Left Heart Syndrome (HLHS). Line drawings provided by Ken K. Wong, Graphic Designer, Mohawk College.

Hypoplastic Left Heart Syndrome (HLHS) is one of the most common and easily diagnosed severe forms of CHD. It is better described as a spectrum of hypoplasia where one end of the spectrum is defined by a slit-like left ventricle and atretic mitral and aortic valve. The opposite end of the spectrum is defined by a patent mitral valve, aortic valve stenosis or atresia and a thick-walled ventricle, calcified and enveloped in endocardial fibroelastosis (Cook et al., 2004). The standard four chamber view demonstrates a small left heart or an echogenic left ventricle due to endocardial fibroelastosis. A small or difficult to visualize left ventricular outflow tract is usually present, see Figure 1-11 (Tworetzky et al., 2001). Alternatively, an enlarged left atrium with a non-contractile, large blood-filled left ventricle may present, which
does not grow as the pregnancy progresses, leaving the left ventricle hypoplastic at birth (Lee & Comstock, 2006).

Hypoplastic Right Heart Syndrome (HRHS) is rarer than HLHS and is defined by an underdeveloped right side of the heart including the ventricle, pulmonary artery, tricuspid and pulmonary valves (Rajiah, Mak, Dubinksy, & Dighe, 2011). Most commonly this is due to pulmonary atresia. Sonographic features include a small, hypertrophied right ventricle with a small or absent pulmonary artery or valve.

A single ventricle is usually (85%) the morphologic left ventricle and represents 2% of congenital heart defects (Rajiah et al., 2011). There is often a second chamber but it is a small rudimentary ventricle which is non-functional. Alternative diagnosis include, large VSD, HLHS or HRHS.

A condition where most of the aorta arises from the right ventricle along with the pulmonary artery and a ventricular septal defect is known as Double Outlet Right Ventricle (DORV). It may be mistaken for TF or TGA with a ventricular septal defect. Frequently the aorta is parallel and to the right of the pulmonary artery (Rajiah et al., 2011). Visualization of the outflow tracts is very important to enable identification of this defect.

A common arterial trunk arising from the base of the heart is commonly known as truncus arteriosus. Typically a truncus overrides a VSD and in the most frequently seen form, Type 1, the pulmonary arteries arise from the trunk. It can be difficult to
differentiate sonographically between truncus arteriosus and pulmonary valve atresia with VSD (Lee & Comstock, 2006).

Total Anomalous Pulmonary Venous Return (TAPVR) represents a rare form of congenital heart disease that, in its obstructed form, presents as a surgical emergency for the newborn (Jaquiss & Tweddell, 2005). The anomalous circulation is characterized by all four pulmonary veins returning to the right atrium rather than to the left atrium. This results in a postnatal closed pulmonary circulation where oxygenated blood recirculates between the right and left heart but never to the systemic circulation. A PFO may allow some mixing of oxygenated and deoxygenated blood (Lee & Comstock, 2006). This anomaly is very difficult to detect in utero and can most reliably be excluded through documentation of pulmonary venous flow into the left atrium (Lee & Comstock, 2006).

Pulmonary stenosis is difficult to diagnose sonographically and may show thickening of the valve leaflets and elevated blood flow velocities across the valve. Consequences of the stenosis may include right ventricle hypertrophy, and a dilated pulmonary artery considered post stenotic dilatation.

A common atrioventricular junction in lieu of separate mitral and tricuspid valve orifices is described as a complete AtrioVentricular Septal Defect (AVSD). It is also referred to as an endocardial cushion defect, or AV canal defect. The sonographic features are defined by a common AV valve and absence of the normal offset of
the tricuspid valve, as well as an inlet VSD and a primum ASD, see Figure 2-4 (Rajiah et al., 2011).

Coarctation of the aorta is a discrete narrowing of the aortic arch distal to the left subclavian artery. It can be difficult to diagnose, while the ductus arteriosus is patent, as it is in the fetus, as this can mask the severity of the narrowed arch. Direct visualization of the transverse arch and aortic isthmus is the best predictor, although indirect evidence includes dilatation of the right heart compared to the left heart (Lee & Comstock, 2006). The ascending aorta is small and the coarctation progresses in utero with increased gestational age (Rajiah et al., 2011).
Chapter 2 Screening for Congenital Heart Disease

Two-Dimensional Imaging Review
Imaging the fetal heart is a very demanding assignment for the ultrasound examiner and interpreting physician. Many variables, both technical and non-technical, will impact the success of the image examination and diagnostic interpretation. Maternal imaging characteristics can profoundly influence exam quality: the fetal lie may make imaging the fetal heart difficult particularly if the fetus is in a downward position facing the maternal spine; low levels of amniotic fluid will reduce the quality of the acoustic window and reduce image quality; and, finally, a very active fetus will hinder the examination of the fetal heart. It may be necessary in some cases to change the maternal position or wait until the fetus changes position to gain access to an adequate acoustic window before the fetal heart examination can be completed. There are however, a number of imaging system controls and settings that can be used to ensure a high quality examination of the fetal heart assuming an adequate acoustic window and suitable fetal lie.

Image quality
The optimisation of image quality depends on the effective management of many technical factors including:

- pre and post processing grey scale
- tissue harmonic processing
- image magnification
- image frame rate
Image quality represents the intersection of three dimensions of image resolution: spatial, contrast and temporal. Spatial resolution is concerned with the ability to define detail in the image. This can be measured or evaluated in all three axes of the acoustic beam, the lateral plane, elevational (thickness) plane and the axial (pulse length) (Hedrick, 2005; Kremkau, 2011; Miele, 2006). Typically acoustic beams are not isotropic, which means that the planes of the acoustic beam are variable in their dimensions and consequently image quality will vary between the axes of the reflectors. The axial dimension is determined primarily by the spatial pulse length which is the product of the transducer frequency and the damping characteristic of the transducer array (Kremkau, 2011). The transducer array typically employs an electronic focus to minimize the beam width and frequently a mechanical or fixed focus is defined for the elevational plane. Acoustic beams are typically narrowest at the focal point and this is where the lateral beam axis can approach the sharpness of the axial plane (Miele, 2006). In nearly all cases the thickness plane is optimized at the focal point but it is typically greater in dimension than either the axial or lateral planes. Optimal imaging of fetal heart structures will depend on the sonographer’s ability to set the focus of the beam to the appropriate anatomic structure to ensure that the structure is visualized (Fredouille, 2007). The sonographer will typically use the highest possible frequency setting to minimize the spatial pulse length and maximize the axial resolution. Inadequate spatial resolution can lead to image “drop out” or blurring of the image.
In terms of contrast resolution, the representation of a visible difference between adjacent reflectors will determine the likelihood of visualization the anatomic structure. Image contrast is a function of image signal relative to image noise (Miele, 2006). The image signal processing is defined as the electronic processing of echo amplitudes representative of anatomic structures. The noise in the image signal can be generated by a variety of acoustic beam interactions in the tissue and signal processing processes (Kremkau, 2011). Noise introduces random fluctuations in the image signal that reduce the image contrast and reduce image quality. In terms of contrast resolution the sonographer will optimize contrast by reducing noise wherever possible and optimizing the signal to enhance the contrast of the relevant image signal elements (Fredouille, 2007). In order to display the magnitude of the echo received by the transducer, the sonographer will apply the dynamic range control. This will determine the amplitude of the image signal and the relative difference in grey shades expressed in the image. The fetal heart is a tubular structure with fluid-filled cavities. The image contrast should be adjusted to accentuate the difference in the visualization of the fluid relative to the walls and outflow tracts. The grey scale can be manipulated at the receiver of the ultrasound system using a dynamic range control. This control will establish the priority of the amplification of signals. It can be adjusted to accentuate the amplification of strong reflectors and minimize the amplification of weak reflectors to ensure a high level of contrast between the blood and the chambers. A secondary
control can also be adjusted on the post processing (after signal storage) function of the ultrasound system. This control can be referred to as grey scale mapping. This signal processing tool represents a manipulation of the grey scale window and level that simultaneously establishes the number of grey shades depicted and selects the range of grey shades presented relative to the image signal. A map that favours a narrow range of signals aligned to the strong amplitudes received from the fetal heart walls and diminishes the weak amplitudes received from the within the chambers will optimize the contrast.

**Pulse-echo Technique**

Sonographic imaging systems use the pulse-echo technique to create real-time images. The imaging transducer, typically a two-dimensional array of piezo-electric crystals emits a series of pulses from the transducer face. Each pulse is transmitted into the soft tissue and at every tissue interface an echo is reflected back to the transducer face based on a difference in acoustic impedance (Kremkau, 2011). Acoustic impedance is the product of the propagation speed of the material and the density. The imaging system assumes an average propagation speed of 1540 m/s and calculates the position of the reflectors based on a simple range equation (Hedrick, 2005). The distance from the source of the acoustic beam is equal to the propagation speed multiplied by the pulse flight time divided by two. Each pulse will generate one scan line. A series of scan lines can be used to construct a two-dimensional image or frame. Multiple frames create a real-time
representation of the tissues. Based on the pulse-echo principle, the maximum frame rate relates to the depth selected by the system user. Typically the maximum number of pulses that can be used in a second is determined by the following relationship:

\[
PRF = \text{Pulse Repetition Frequency (Hz)}
\]

\[
c = \text{Propagation speed (cm/s)}
\]

\[
d = \text{Depth (cm)}
\]

\[
PRF = \frac{c}{2d}
\]

The assignment of scan lines/frame is usually determined by the manufacturer. The frame rate depends on the relationship between the PRF and depth, maintaining the minimum depth setting possible to adequately visualize the relevant anatomy to support the maintenance of a high frame rate.

To ensure adequate visualization of the movement of the fetal heart with a minimum of blurring, the frame rate should be set as high as possible (Fredouille, 2007). It is important to note that the depth setting is the key input to determine the number of scan lines available in a second and this means it can be a useful proxy for frame rate. Minimizing the depth setting provides the system with the maximum available frame rate and this defines the limits of temporal resolution.

**Image Formation**
Image formation is based on the registration of the acoustic scan lines as a two-dimensional matrix or frame. Each echo is translated into a voltage-amplitude based on a piezo-electric transformation at
the transducer face. The representation of amplitudes on the image display depends on the nature of the acoustic beam tissue interactions (Hedrick, 2005).

In general terms, three acoustic beam/tissue interactions create echos which are used to form the image:

1. Specular (mirror) reflections
2. Scattering reflections
3. Rayleigh Scatter

Specular reflectors are smooth and large relative to the wave front of the acoustic beam. Specular reflectors are strong reflectors and generate angle-dependent reflections (Kremkau, 2011). Tissue parenchyma scatters the acoustic beam generating weak reflections that create coherent wave interference patterns in the image.

The dominant forms of reflection relative to imaging the fetal heart are specular and Rayleigh scatter. Since specular reflectors behave as acoustic mirrors they are highly sensitive to the angle of acoustic beam insonation.

Red blood cells interact with the acoustic beam as very weak Rayleigh scatter (Kremkau, 2011). This form of reflection generates very low amplitude reflections that are highly sensitive to the frequency of the acoustic beam. The intensity of the reflection is proportional to the frequency to the fourth power (Miele, 2006). Typically, for grey-scale imaging, Rayleigh scatter is depicted as anechoic.
Image Processing

Most frequently fetal cardiac imaging is performed by using a 2-5 MHz curvi-linear transducer array employing broad bandwidth signal processing. Typical frame rates can vary between 15-90 Hz depending on the depth and preset parameters. Image enlargement is a very important capability to provide adequate visualization of the fetal heart. Ideally the fetal thorax will fill 2/3 of the image display. There are two methods for image enlargement, write zoom and read zoom. Write zoom magnification defines an image matrix solely based on the zoom box size (Kremkau, 2011). This method preserves optimal spatial resolution but it requires the sonographer to perform the enlargement of the image in real-time. Alternatively, the image maybe zoomed in real-time or after the image is frozen by using a “read” zoom approach which multiplies stored pixel values to create a larger image. This method will rapidly sacrifice image quality as the image increases in size (Kremkau, 2011).

Images stored in the system memory can be recorded on film or disk as static frames representing the curvilinear field of view. Alternatively, a series of images can be stored as a series of frames over time typically 1-10 seconds duration. These are typically described as cine-loops or cine-clips and may include colour and/or spectral Doppler along with grey scale image information. A grey scale, four second cine-loop generates an AVI file size of approximately 35-50 megabytes, which can be easily compressed to a 1-3 megabyte MP4 format file.
Tissue harmonic imaging is a powerful signal processing tool that reduces acoustic noise and enhances contrast resolution (Miele, 2006). As the acoustic beam propagates in soft tissue, the central axis of the acoustic beam where the intensity of the beam is greatest distorts the wave creating harmonic frequencies that echo back to the transducer array as multiples of the fundamental frequency. It is possible to extract the harmonic echoes using either pulse inversion or RF processing as distinctly different from the fundamental frequency (Miele, 2006). Since the harmonic frequencies are generated in tissue, they are only distorted on the path back to the transducer array compared with the fundamental frequency which is distorted as it passes through the tissue and echoes back. Furthermore, the harmonic echoes return only along the path of the acoustic beam and do not contribute off-axis acoustic noise to the image (Miele, 2006).

Optimal imaging of the fetal heart requires effective management of image contrast resolution, temporal resolution and spatial resolution (Fredouille, 2007). The optimal image settings to balance the image quality parameters described above are summarized in Table 2-1.
Table 2-1

Optimal settings for grey scale imaging the fetal heart and their impact on image quality.

<table>
<thead>
<tr>
<th>System Control</th>
<th>Optimal Setting</th>
<th>Spatial Resolution</th>
<th>Contrast Resolution</th>
<th>Temporal Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth</td>
<td>Minimum possible</td>
<td>Indirect impact</td>
<td>No impact</td>
<td>Direct impact</td>
</tr>
<tr>
<td></td>
<td>Maximum possible</td>
<td>Direct impact</td>
<td>No impact</td>
<td>No impact</td>
</tr>
<tr>
<td></td>
<td>Set at structure of interest</td>
<td>Direct impact</td>
<td>No impact</td>
<td>No impact</td>
</tr>
<tr>
<td>Magnification</td>
<td>Fetal thorax should fill 2/3 of the field of view</td>
<td>Direct impact</td>
<td>No Impact</td>
<td>No impact</td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>High contrast</td>
<td>No impact</td>
<td>Direct impact</td>
<td>No impact</td>
</tr>
<tr>
<td>Grey Scale Maps</td>
<td>High contrast</td>
<td>No impact</td>
<td>Direct impact</td>
<td>No impact</td>
</tr>
<tr>
<td>Tissue Harmonic Imaging</td>
<td>Highest possible</td>
<td>Indirect impact</td>
<td>Direct impact</td>
<td>Minimal impact</td>
</tr>
<tr>
<td>Frame Rate</td>
<td>60-90 Hz.</td>
<td>No impact</td>
<td>No impact</td>
<td>High impact</td>
</tr>
</tbody>
</table>

Doppler imaging

The movement of tissue and/or blood can be coded in colour overlying the grey scale image or registered as a two-dimensional spectral trace adjacent the grey scale image in real-time. Although the instrumentation and signal processing techniques applied to colour and spectral Doppler techniques vary considerably, the underlying physical principles are similar. The echoes returning from moving interfaces, tissue or blood cells are shifted in frequency as defined by the Doppler effect. The Doppler effect represents a change in the perceived frequency received by the transducer relative to the transmitted frequency (Kremkau, 2011). The magnitude of the shift depends on the both the angle and
speed of the moving reflector. The Doppler equation summarizes the key variables that influence the magnitude of the perceived shift as follows:

$$F_d = \text{Doppler shift (Hz)}$$

$$f = \text{Transmitted frequency (Hz)}$$

$$\theta = \text{the angle between the acoustic beam and the reflector direction}$$

$$v = \text{Reflector speed (cm/s)}$$

$$c = \text{Propagation speed (cm/s)}$$

$$F_d = f \times \cos \theta (2 \times v) \div c$$

As in all signal sampling processes, aliasing of the Doppler signal is a phenomenon that occurs when the Nyquist limit is violated. The Nyquist limit specifies the minimum number of samples that must be acquired relative to the frequency of the image signal. The minimum number of samples/cycle is equal to two (Miele, 2006). Nyquist Limit can also be defined as the maximum detectable Doppler shift without aliasing.

$$F_d(\text{maximum}) = PRF \div 2$$

When the sampling frequency falls below the minimum threshold, the displayed image will not register the full frequency shift. This can be observed in both colour and spectral modes of observation as illustrated in Figure 2-1.
Figure 2-1

Aliasing can be observed in the colour coding of the aqua-blue segments of the colour map in this image. The PRF is set at 1500 Hz and where blood flow generates a Doppler shift > than 750 Hz, the colour coding reverses on the colour spectrum. A similar phenomenon is observed in spectral Doppler waveforms.

Doppler image processing

Image formation during Doppler processing relies on the pulse repetition frequency which is equal to the propagation speed divided by two times the depth setting. This inverse relationship implies that an increase in depth reduces the pulse repetition frequency and hence the number of samples that can be used to form the two dimensional image and sample the Doppler shift.

For this reason, most frequently sonographers will alternate between the live two dimensional image and the live spectral image and this technique is commonly referred to as duplex imaging; simultaneous display of colour and spectral images is described as triplex imaging. Triplex imaging is not often used for imaging at depths greater than 5-10 cm since the frame rate loss creates a
loss of coherence between the two modes of imaging. Colour sampling is usually set at a pulse packet of between 4-32 pulses/scan-line. Since colour imaging is performed at the same time as the grey scale image is displayed, the likelihood of aliasing is much greater compared with spectral Doppler imaging. The relationship between pulse packet size, image depth, frame rate and aliasing relative to image resolution are evident in Table 2-2.

Colour Doppler makes it possible to provide a map of tissue movement or blood flow. In most instances, colour Doppler is used to map blood flow and this is a very helpful tool to distinguish the presence of flow, quality of flow, turbulent or laminar and the speed of flow. Spectral Doppler can provide quantitative values representative of blood flow speed (Kremkau, 2011).

An alternative to colour or directional Doppler imaging is power or amplitude imaging. This technique is very similar to colour Doppler imaging except that flow speed and direction are not provided. Instead of splitting the Doppler shift signal in to two channels to provide directional information, the entire signal is processed and mapped according to the amplitude of the echoes (Miele, 2006). This technique is typically used to detect low or slow blood flow due to the enhanced sensitivity associated with the signal processing methods.

While colour Doppler is a very useful tool to map blood flow and describe flow dynamics, it does have significant limitations and drawbacks which must be considered. The use of colour Doppler
constrains the frame rate and limits the temporal resolution available for assessing fetal heart. Furthermore, inappropriate colour gain or PRF will result in significant noise overlaying the grey scale image and this may limit the assessment of important anatomical structures including the interventricular septum and the chamber walls.

Optimal Doppler imaging parameters for the fetal heart are described below in Table 2-2

**Table 2-2**

Doppler system controls and the impact on image quality (Kremkau, 2011).

<table>
<thead>
<tr>
<th>System Control</th>
<th>Optimal Setting</th>
<th>Spatial Resolution</th>
<th>Contrast Resolution</th>
<th>Temporal Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth</td>
<td>Minimum possible</td>
<td>Indirect impact</td>
<td>No impact</td>
<td>Direct impact</td>
</tr>
<tr>
<td>PRF/Velocity Scale</td>
<td>As high as needed to avoid aliasing</td>
<td>Direct impact</td>
<td>No impact</td>
<td>Direct impact</td>
</tr>
<tr>
<td>Sector Width</td>
<td>Set at structure of interest</td>
<td>Direct impact</td>
<td>No impact</td>
<td>Direct impact</td>
</tr>
<tr>
<td>Pulse Packet Size</td>
<td>Set low</td>
<td>Direct impact</td>
<td>No Impact</td>
<td>Direct impact</td>
</tr>
<tr>
<td>Colour gain</td>
<td>Just high enough to fill the vessel or chamber</td>
<td>Direct impact</td>
<td>No impact</td>
<td>No impact</td>
</tr>
<tr>
<td>Threshold</td>
<td>Just enough to fill the vessel or chamber</td>
<td>Direct impact</td>
<td>No impact</td>
<td>No impact</td>
</tr>
</tbody>
</table>

**Three dimensional imaging STIC and Matrix tools**

Although two-dimensional imaging of the fetal heart can be routinely expected to provide high quality images and a real-time perspective, the complexity and relationships of fetal heart anatomy can be difficult to resolve consistently as single, static images for
review by the interpreting physician. A three-dimensional view of the fetal heart would resolve some key limitations of two-dimensional imaging including:

- Inability to display views of the fetal heart obstructed by the fetal thorax, primarily the coronal axis
- Requirement to mentally transform two-dimensional relationships into three-dimensional impressions, a highly subjective and user-dependent process
- Increased variability of measurements (Fenster, Downey, & Cardinal, 2001).

Many different approaches have been used over the past twenty years to acquire three-dimensional images. These can be categorized as, mechanical, free-hand and a unique free hand approach employing a two-dimensional phased array of transducers (Fenster et al., 2001). Mechanical methods of three-dimensional imaging have fallen out of favour in recent years due to their size, bulkiness and advances in free-hand techniques. Within the realm of fetal imaging, two free hand imaging techniques have become dominant: Real-Time three-dimensional imaging and Spatial-Temporal Image Correlation (STIC).

Three new developments have emerged from the maturation of sonographic, three-dimensional imaging technology. Two of these relate to the method of image acquisition and the third relates to the off-line analysis of the image volume. The Spatial-Temporal Image Correlation (STIC) acquisition technique generates a three-
dimensional cine-loop while a live, three-dimensional imaging method uses a two-dimensional matrix of transducers to generate a live, three-dimensional image. Distinctive advantages and disadvantages can be identified for the STIC and live three dimensional techniques respectively while the ability to analyze the fetal heart in three dimensions in real-time, off-line provides the specialist with the necessary data to identify congenital heart defects after the patient has left the imaging facility or from a location geographically distant from the site of acquisition.

Development of techniques for imaging the fetal heart in three dimensions in real-time have addressed at least two of the key limitations of two-dimensional imaging. Visualizing the anatomy in multiple planes simultaneously provides the clinician with the tools necessary to establish the spatial relationships between the relevant cardiac structures such as the cross-over of the RVOT and LVOT. In addition the real-time characteristics, wall motion and synchronicity can be established in real-time.

**Acquiring a Three-Dimensional Volume**

Formation of a three dimensional image using acoustic technology poses unique challenges for engineers and physicists. Sonographic images are two dimensional slices of variable thickness. The axial, lateral and thickness planes vary in dimensions over depth and when they are used to produce volume data sets they generate asymmetric voxels. The thickness plane is typically the largest dimension and reconstruction of this plane generates the lowest image quality of the three planes.
Presently there are two different techniques that can be used to acquire volume datasets of the fetal heart. The most well-known technique is known as spatial-temporal image correlation (STIC) and typically uses an internally motorized single-dimensional array of crystals. Another technique that has been popular for imaging adult hearts is known as a matrix array, capable of live three-dimensional imaging. Although the matrix array was developed to image adult hearts, numerous investigators have begun the process of assessing its value in imaging fetal hearts. Each of these techniques can be defined by the strengths and weaknesses that impact their effectiveness in imaging fetal hearts.

**STIC**
The STIC technique acquires a volume of image data using an automated scan head that slowly sweeps through a pre-selected arc (DeVore, Falkensammer, Sklansky, & Platt, 2003).

As described in the seminal article by Devore et al., the linear array of elements acquires image data at a very high frame rate of approximately 150 frames/s. The acquisition time can be adjusted between 7.5 – 15 seconds. Acquisition over a longer period of time allows the algorithm to acquire more images and optimize image quality. As an example, a 10 second acquisition at a frame rate of 150 frames/s will generate 1500 image slices of the fetal heart as it moves through 23 cardiac cycles assuming a fetal heart rate of 140 bpm. The STIC algorithm analyzes the periodic motion of the heart as it contracts and expands to determine the average heart rate. Multiple cardiac volumes will be generated from the correlation
between image slices and the heart rate. The image slices are registered according to the phase of the cardiac cycle. A complete acquisition represents a cine-loop of multiple cardiac volumes. For this reason, significant changes in fetal heart rate or fetal movement will result in a failed reconstruction (DeVore et al., 2003). The STIC acquisition technique generates a cine-loop comprised of multiple volume reconstructions. This allows the viewer to interrogate the heart in three-dimensions as a real-time cine-loop.

Image analysis involves the use of the Multi-planar Reconstruction (MPR) technique. The volume can be interrogated in any plane and the relationship between orthogonal planes is maintained (Yagel, Cohen, Shapiro, & Valsky, 2007). It is possible to reconstruct images of the cardiac outflow tracts and establish their relationship without rescanning the patient. Additional tools allow the viewer to subtract structures from the image and improve visualization of targeted anatomical structures.

**Live 3D**
The main differences between the STIC technique and the matrix transducer are related to the beam formation and processing of acquired image slices. The matrix uses up to three thousand tiny crystals to simultaneously transmit and receive acoustic pulses, see Figure 2-2. The beam is electronically controlled and steered in real-time acquiring pyramidal volumes (Stetten & Tamburo, 2001). A significant development enabling the success of this technique relates to the number of miniaturized circuit boards embedded within the probe handle providing the capacity to perform signal
processing prior to the signal returning to the main sonography system. The sheer number of slices required to generate sufficient pyramidal volumes for real-time display imposes a significant signal processing challenge. Parallel processing the acoustic beam at a rate of 16:1 allows the system to acquire sufficient slices to generate real-time pyramidal volumes at clinically useful depths of penetration (Appareti, 2003). The electronic beam formation generates nearly symmetric voxels but suffers from lower SNR relative to the STIC technique.
Volume Image Analysis
Due to the complexity of congenital heart defects, and in many cases their subtle characteristics, expert consultation is usually required. The standard image acquisition techniques usually involve static image slices stored on film or electronically. In more rare instances video or real-time sequences are acquired. In any case consultation usually requires a rescan at the referral center, a process that extends the period of diagnostic uncertainty and may add significant emotional stress to the prospective parents. In addition to the emotional distress, the additional resources and
travel may significantly add cost to the patient and healthcare system.

**Off-line Analysis**

Acquisition of scanned volumes may be able to alleviate some of these limitations through the application of telemedicine for consultation. The three-dimensional volume can be transmitted and reviewed remotely using a broadband internet connection. The consultant is then able to examine the fetal heart in multiple planes and in motion in much the same way the sonographer was able to visualize the anatomy in real-time. A number of studies have trialed this concept (Chan, Soong, Lessing, Watson, Concotta, Baker, et al. 2000). In 2000 Kratochwil, Lee and Schoisswohl were able to demonstrate the feasibility of this concept and found that 20:1 and 30:1 wavelet image compression techniques could be applied without a discernable loss of information (Kratochwil, Lee, & Schoisswohl, 2000). In another study performed in Australia, image volumes were successfully transmitted from Townsville to Brisbane a distance of 1500 km. This eliminated the need for physical referral of 24/71 patients resulting in a significant cost saving to the patients and healthcare system. In the most comprehensive evaluation published to date, Vinals et al were able to demonstrate that STIC volumes could be acquired by operators inexperienced in fetal echocardiography and transmit them through the internet from multiple remote locations in Chile to a referral centre in Santiago Chile (Viñals, Tapia, & Giuliano, 2002). This allowed the specialists the opportunity to rule out and confirm a diagnosis remotely. In
addition a web camera and e-mail were used to advise patients as
to the benefits of referral to tertiary care centers for those with
CHDs diagnosed. Evidence is rapidly accumulating to support the
concept of using telemedicine and three dimensional volume
analysis as a means of gaining an expert consultation without the
need for physical referral or rescanning. For many countries this is
a technique that may alleviate the challenge of providing advanced
healthcare to populations geographically distant from specialists
located in tertiary health centers.

Summary
The development of two distinct three-dimensional imaging
techniques coupled with the capability of remote analysis via
telemedicine has the potential to transform the methods used to
manage patients that otherwise require referral to specialized fetal
treatment centers. The benefits of imaging the fetal heart using
three dimensional sonographic imaging may include increased
detection of CHD and enhanced diagnostic capabilities. These
imaging capabilities may be offset by the increased cost and
accessibility of three dimensional imaging systems and the
relatively steep learning curve associated with their use.
**Sonographic Features and Techniques for Early Detection**

The impact of congenital heart disease varies widely depending on the specific form it takes. In some cases, the chambers of the heart may be entirely normal in appearance and the defect may only be evidenced in the outflow tracts of the heart. For example, congenital heart disease relating to the outflow tracts such as dextro-transposition of the great arteries may only be detected at their origins and frequently are not detected by the four chamber view, see Figure 2-3.
Figure 2-3

The four chamber view in 2A, appears normal, in 2B sweeping into the outflow tracts reveals a parallel orientation of the LVOT and RVOT indicating a Dextro-Transposition of the Great Arteries. Additional images extracted from the same cine-loop sweep, demonstrate the branching associated with the aorta 2C, arising from the right ventricle and a pulmonary artery arising from the left ventricle in 2D. Line drawings provided by Ken K. Wong, Graphic Designer, Mohawk College.

Since static images of the fetal heart represent only very thin slices of the fetal heart it is very important that the fetal heart is assessed in real-time and interrogated completely in contiguous slices. The diversity and relative complexity of congenital heart defects demands considerable skill of the sonographer and interpreting physician to ensure a complete examination.
Impact of Early Detection
The majority of deaths from congenital defects in childhood can be attributed to congenital heart disease (CHD). CHD is six times more common than chromosomal abnormalities and four times more common than neural tube defects (Carvalho, Mavrides, Shinebourne, Campbell, & Thilaganathan, 2002). The most common cause of birth defects, CHD is most frequently reported with an incidence of 0.8% of all live births (Hoffman & Kaplan, 2002). Improvements based on technical advances in the management and therapy of CHD has resulted in a shifting of the outcomes such that adults living with CHD outnumber the number of children with CHD (Hoffman, Kaplan, & Liberthson, 2004).

Prenatal detection of CHD provides a number of advantages relative to postnatal identification.

1. Counselling, and the continuance of a viable pregnancy
2. Monitoring of pregnancy and treatment
3. Assessment for extracardiac disease and genetic associations
4. Decrease morbidity in some cases, reduction in fetal neurological impact

Some of the benefits of routine obstetrical screening have been found to include maternal psychological effects, as well as an increased connection between the unborn child and enhanced maternal-fetal bond (Sklansky et al., 2002). The visualization of the fetus along with a normal screening result has been found to decrease maternal anxiety and increase satisfaction (Sklansky et
al., 2002). Conversely, an abnormal result has the effect of decreasing maternal happiness and increasing anxiety. As stated by Menahem et al., “Diagnosis was made at 17 weeks. The baby was active.” so that attachment has already begun between the mother and her unborn infant. As one father in the same study observed “my wife loved the baby so many months and worked hard to keep it, to find out things were not right—is difficult beyond belief” (Menahem & Grimwade, 2003).

In the long term, compared with women who were not diagnosed prenatally, there was a more favourable impact on maternal happiness. Mothers felt less responsibility for the CHD and tended towards improved relationships with the infant’s fathers after prenatal diagnosis (Sklansky et al., 2002). The early detection of CHD ensures that there will be an opportunity to provide a clear and accurate picture of the prognosis and outline treatment options to the parents. The clinician must be able to base the prognosis on a number of factors, not solely on the diagnosis. These factors include; the security of the diagnosis, stage in gestation, potential for change, and association with extracardiac malformations and known results of treatment (Allan & Huggon, 2004). The counselling opportunity provided by prenatal detection expands the range of options to parents which may include continuance of the pregnancy, continuance with therapy and/or possibly termination of the pregnancy. Gestational age at the time of diagnosis is one of the strongest predictors of pregnancy termination. An early diagnosis is associated with termination in up to 70% of cases, the probability of
termination is inversely related to the percentage of early diagnosis in a population (Germanakis & Sifakis, 2006).

For those parents that choose to continue the pregnancy, early detection provides the opportunity to meet with perinatologists, and cardiac specialists engaging in relaxed discussions related to prospective interventions. These discussions may provide the parents with a greater sense of control, while the healthcare team may be in a better position to minimize potential complications, adjusting the timing of the delivery either by induction, caesarean section or the use of tocolytic agents to allow greater maturation of the lungs, if required (Jaquiss & Tweddell, 2005). Often the infant is able to make a much less disruptive entry into post natal life through the provision of prostaglandin infusions, respiratory support and intensive monitoring as required (Jaquiss & Tweddell, 2005).

A number of severe forms of CHD have been found to benefit from prenatal diagnosis. Tworetzky et al, reported that surgical outcomes for HLHS improved after fetal diagnosis. In a study of 88 patients, all 33 cases that were diagnosed prenatally survived surgery whereas only 25/38 that were postnatally diagnosed survived (Tworetzky et al., 2001). Without prenatal diagnosis, most infants born with HLHS experience delays in diagnosis and appropriate resuscitation. This may lead to systemic hypoperfusion, shock and organ damage hindering the long term survival prospects (Tworetzky et al., 2001). These findings are supported by Satomi et al in their study of HLHS, which discussed finding improvements in
preoperative conditions and avoidance of ductal shock (Satomi, Yasukochi, Shimizu, Takigiku, & Ishii, 1999).

Bonnet et al, determined that prenatal detection of TGA reduced neonatal morbidity and mortality. A ten year study comparing 68 neonates with prenatal diagnosis and 250 neonates without prenatal diagnosis, identified significant delays in access to the pediatric cardiology unit, increased postoperative mortality and longer postoperative stays for those diagnosed post natailly (Bonnet et al., 1999). Prenatal diagnosis of coarctation of the aorta was found to improve survival rates and reduce morbidity (Franklin, 2002). An examination of 217 neonates with hypoplastic left heart syndrome and 422 with transposition of the great arteries found that those with a prenatal diagnosis who underwent surgery had objective indicators of lower severity of illness preoperatively (Kumar, Newburger, Gauvreau, Kamenir, & Hornberger, 1996). Although the prenatally diagnosed group experienced improved preoperative condition, in this study, postoperative outcome did not differ between the two groups (Kumar et al., 1996).

Current Techniques
The type of CHD and the medical practice performing the screening are identified as key factors by a number of studies (Friedberg et al., 2009; Jaeggi et al., 2001; Wong, Chan, Cincotta, Lee-Tannock, & Ward, 2003). Not surprisingly a number of studies have shown increased detection of CHD at tertiary care centres as compared to community screening centers (Friedberg et al., 2009; Grandjean et al., 1999; Jaeggi et al., 2001; Stumpflen, Stumpflen, Wimmer,
The screening of CHD can range from a basic exam, extended exam to include additional views such as the three vessel view, and the inclusion of Doppler and three-dimensional imaging techniques.

**Static Images**
The basic exam consists of a recording of the four-chambers of the fetal heart as a cross-sectional image. As noted by Chaoui, this approach has not led to widespread improvement in the detection of heart defects (Chaoui, 2003). In his analysis he identified four reasons for this outcome, the primary one being the fact that many defects cannot be visualized in the four-chamber view, see Table 2-3 (Chaoui, 2003). In an extended effort to identify cono-truncal defects, the extended exam includes views of the left and right outflow tracts (ACR Guidelines and Standards Committee, American Institute of Ultrasound in Medicine, 2003; Lee et al., 2008). Yagel et al proposed the acquisition and review of five cross-sectional images as a means of improving and simplifying the screening process (Yagel, Cohen, & Achiron, 2001). This approach ensures that many of the key anatomic structures are represented beginning with the abdominal situs and ending with a view of the three vessels, the pulmonary trunk, the aorta and the superior vena cava (Yagel et al., 2001). In a similar line of reasoning, Yoo et al, have proposed the inclusion of the three vessel view as an element of every screening examination (Yoo, Lee, Kim, Ryu, Choi, Cho, 1997). The three vessel view is very effective in identifying many of the abnormalities associated with the outflow tracts and great

Table 2-3

Prenatal Detection Rate of Anomalies by View and Frequency of Incidence. (Jaeggi et al., 2001)

<table>
<thead>
<tr>
<th>Anomaly</th>
<th>Four chamber view (%)</th>
<th>Outflow tracts (%)</th>
<th>Subjects total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detected by Four chamber view</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Complete Atrioventricular Septal Defect</td>
<td>12 (15.4)</td>
<td></td>
<td>78</td>
</tr>
<tr>
<td>Hypoplastic Left Heart</td>
<td>12 (44)</td>
<td></td>
<td>37</td>
</tr>
<tr>
<td>Total Anomalous Pulmonary Return</td>
<td>0</td>
<td></td>
<td>23</td>
</tr>
<tr>
<td>Mitral or Tricuspid atresia</td>
<td>11 (50)</td>
<td></td>
<td>22</td>
</tr>
<tr>
<td>AV septal defects</td>
<td>7 (44)</td>
<td></td>
<td>16</td>
</tr>
<tr>
<td>Pulmonary atresia (intact ventricular septum)</td>
<td>5 (31)</td>
<td></td>
<td>16</td>
</tr>
<tr>
<td>Ebsteins anomaly</td>
<td>7 (46.7)</td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>5 (50)</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>Complete heart block</td>
<td>5 (83.3)</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>Corrected transposition</td>
<td>2 (40)</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>Total</td>
<td>66 (29)</td>
<td></td>
<td>229</td>
</tr>
<tr>
<td>Detected by Outflow views</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tetralogy of Fallot</td>
<td>11 (10)</td>
<td>110</td>
<td></td>
</tr>
<tr>
<td>Aortic arch obstruction</td>
<td>2 (2.6)</td>
<td>78</td>
<td></td>
</tr>
<tr>
<td>Dextro-Transposition great arteries</td>
<td>0</td>
<td>77</td>
<td></td>
</tr>
<tr>
<td>Ventricular septal defect</td>
<td>4 (5.3)</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>Double outlet right ventricle</td>
<td>5 (18.5)</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td>Aortic stenosis</td>
<td>5 (20)</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Pulmonary stenosis</td>
<td>2 (8.7)</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>Truncus arteriosus</td>
<td>0</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>Aortic-pulmonary window</td>
<td>0</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>29 (6.7)</td>
<td>430</td>
<td></td>
</tr>
</tbody>
</table>

Although the use of multiple cross-sectional planes and the three vessel view have the potential to demonstrate a great deal of the fetal heart anatomy, these views have not been adopted by a majority of screening centres. Acquiring static images of the outflow tracts has proven to be more difficult than acquiring the four-
chamber view where all of the anatomy can be seen in one plane (Sklansky, 2007). Furthermore, static images do not provide a real-time perspective of the fetal heart and this remains a significant limitation of this imaging mode. Sklansky has proposed a modified approach using cine-loops that may address some of the challenges associated with acquiring multiple static images (Sklansky, 2007).

**Importance of Cine-Loop Sweeps**
The sonographic features of severe CHD can usually be captured as static images, once the disease is identified; however, it is a challenge in many cases to identify CHD using only static images. In Figure 2-3 the presence of parallel outflow tracts is documented as a series of static images. It is worth noting that in isolation, some of these static images may appear normal whereas in the context of a cine-loop the aggregate set of images defines a relationship between the outflow tracts that is more difficult to establish with static images only. The four chamber image in this set is normal in terms of the situs, axis and relative size of the fetal heart compared with the thorax. The image of the LVOT in panel D of Figure 2-3 could also be misinterpreted as normal, key static images are depicted in B and C. Should these images be unavailable, the identification of CHD could be missed.
In this image pair A and B static images taken from the same cine-loop sweep represent very different structural realities. A ventricular septal defect associated with Tetralogy of Fallot is indicated by the shaded area in image B, the septum appears to be intact in image A extracted from the same cine-loop sweep. Transducer frequency, 2.3-4.6 MHz, Tissue Harmonic Imaging, 80 Hz frame rate. Line drawings provided by Ken K. Wong, Graphic Designer, Mohawk College.

Another example where a cine-loop provides more value compared with only a set of static images is illustrated in Figure 2-4. In this example it is clear that the ventricular septal defect is evident in the anterior aspect of the chamber and not the posterior aspect. This could be easily misrepresented as a normal case if only the static image as in figure A is provided for interpretation. Similarly, in Figure 2-5, the atrioventricular septal defect apparent in image B could easily be overlooked if only image A is provided for interpretation. Sweeping the acoustic beam through the fetal heart, acquiring thirty or more images/second, provides a more complete set of images for interpretation. In addition, the cine-loop sweeps provide many more opportunities to assess the relationship between fetal cardiac structures and to assess the dynamics of the
fetal heart, myocardial contractility, valve motion and the synchrony of the chambers.

Figure 2-5
In this image pair taken from the same cine-loop sweep the interventricular septum appears intact in A, in the adjacent image B, the septum is not intact. This represents an Atrioventricular Septal Defect (AVSD). Line drawings provided by Ken K. Wong, Graphic Designer, Mohawk College.

Colour Doppler
The inclusion of colour Doppler imaging in every fetal cardiac examination was proposed by Chaoui & McEwing in order to increase the speed and accuracy of the examination (Chaoui & McEwing, 2003). In their review article, they identify three cross-sectional planes to simplify the colour Doppler examination; the four chamber, five chamber view and three vessel views (Chaoui & McEwing, 2003). Copel et al, found that in 29% of cases the use of colour Doppler was essential for an accurate diagnosis (Copel, Joshua, Morotti, Hobbins, 1991). The inclusion of colour Doppler cine-loops has been found to assist in clearing the screening views of the heart in difficult cases (Poole et al., 2013). In a pilot study, Scott et al examined the potential for including a colour Doppler
cine-loop of the three vessel view in a routine obstetrical screening protocol (Scott et al., 2008). The results of this study determined that the colour cine-loop lengthened the examination time significantly and adversely affected the quality of the grey scale features due to bleeding of colour and challenges associated with optimizing the colour Doppler controls (Scott et al., 2008).

**Three-Dimensional Imaging**

The Spatio-Temporal Image Correlation (STIC) technology enabling the three-dimensional imaging of the fetal heart as a cine-loop volume has been commercially available for approximately ten years (Goncalves, 2005). The STIC methodology uses a slow sweeping acquisition of many image planes over a 7.5-15 second time interval. The mean heart rate is calculated and the images are reformatted according to their correlation to the cardiac cycle (Chaoui & Heling, 2005; DeVore et al., 2003). This technique generates a cardiac volume which can be reviewed as a cine-loop at any speed and images can be generated from the volume in any plane (Chaoui & Heling, 2005; DeVore et al., 2003; Gonçalves et al., 2003). Interrogating the fetal heart in any plane within a moving cine-loop provides a number of advantages compared to two-dimensional imaging. This would include the ability to review unlimited images, correlate images between orthogonal planes, and accessing novel planes such as the enface view of the cardiac valves obtained through the coronal plane (Goncalves, 2005).

A number of closely related innovations have been designed to enhance the relationship between anatomic structures, particularly
the outflow tracts. Those that leverage the STIC technology include, Doppler and Doppler angiography and tomographic imaging. Doppler imaging relies on the phase shift associated with the movement of reflectors within the path of the acoustic beam (York & Kim, 1999). The phase shift is angle dependent, reflections from moving reflectors at 90 degrees relative to the acoustic beam axis do not shift the phase of the frequency and are typically not visualized with Doppler processing (York & Kim, 1999). In contrast, Power Doppler or Doppler Angiography techniques process the magnitude of the phase shift and do not determine directionality of the reflectors. The loss of directional information is compensated by significantly enhanced sensitivity to the presence of moving reflectors (Chaoui & Kalache, 2001). In 2009, Tonni et al examined the feasibility of including three-dimensional and Doppler angiography of the great arteries in the second trimester examination (Tonni, Centini, & Taddei, 2009). It was found that three-dimensional imaging and Doppler can enhance the visualization rate of the great vessels, although it is perceived to be premature to include these techniques in routine examinations (Tonni et al., 2009). According to Tonni et al., the technique should be reserved for targeted cases where the two-dimensional examination is incomplete (Tonni et al., 2009).

Tomographic imaging leverages the unique volume dataset provided by the STIC technology. Tomographic imaging provides the examiner with the ability to visualize an array of image slices represented as a panel with a reference image available to
correlate the position of the slices relative to the image volume (Espinoza et al., 2008). Espinoza et al provide a standardized method that can be used to reproduce the most clinically relevant and valuable images using commercial available software processing (Espinoza et al., 2008). In a step further to minimize operator training and dependency, Abuhamad et al evaluated an automated software program that demonstrated the capability of auto generating tomographic images from standardized volumes (Abuhamad, Falkensammer, Reichartseder, & Zhao, 2008). In this evaluation the software demonstrated a successful depiction of tomographic slices in over 90% of each of the three cardiac planes: the five chamber view, the aorta, the right ventricular outflow plane, and the pulmonary artery, along with the abdominal circumference, and the plane capturing the stomach (Abuhamad et al., 2008).

Summary
The detection of CHD during routine obstetrical screening remains a diagnostic challenge. Unfortunately, improvements in sonography instrumentation and systems including colour Doppler and three-dimensional imaging techniques, have not resulted in improvements in the detection of CHD (Shen & Yagel, 2010). Friedberg et al reports that where screening is performed in nearly all patients in northern California the detection of major CHD’s ranges from 20%-82%, with an average rate of 28% detection (Friedberg et al., 2009) In some cases, the early detection of CHD has significant impact on the morbidity of neonates born with CHD (Bonnet et al., 1999; Franklin, 2002; Satomi et al., 1999). For parents, early detection
can provide an opportunity for counselling and improved understanding of the prognostic details of their pregnancy. Early detection also provides an opportunity for improved management of the delivery and the ability to possibly minimize complications.

A number of methods have been proposed to improve the detection rate of CHD including the three vessel view by Yoo, the use of colour Doppler as proposed by Chaoui and a variety of three-dimensional imaging techniques (Chaoui & McEwing, 2003; DeVore, Polanco, Sklansky, & Platt, 2004). Unfortunately, widespread adoption of each of these techniques has been limited. Access to three-dimensional sonography systems is limited and the optimal use of these systems to consistently acquire three-dimensional images of the fetal heart requires significant additional training (Roberts, 2008; Tonni et al., 2009).

The reliance on static images for the assessment of the fetal heart imposes a significant limit to the screening of CHD during routine obstetrical examinations. Using static images only, the interpreting physician will not be able to assess the function or anatomic relationships between cardiac structures. Alternatively, using cine-loop sweeps provides the sonographer and the interpreting physician with the opportunity to perform a dynamic assessment of the fetal heart.

The use of cine-loops and real-time assessment of the fetal heart has been suggested by a number of authors as a means of improving the screening process (Mcgahan et al., 2007; Sklansky,
The use of cine-loop sweeps will provide many more images of the fetal heart, establishing critically important anatomical relationships, and cardiac dynamics. Furthermore, this approach has the potential to improve the detection of CHD during screening by reducing the variability in the image data recorded and standardizing the assessment of the fetal heart.

The acquisition of cine-loop sweeps through the fetal heart in lieu of static images only has the potential to increase the detection of CHD without imposing additional requirements for examiner training or additional imaging techniques such as colour Doppler or three-dimensional imaging. Standardizing the assessment of the fetal heart and evaluating the functional characteristics of the fetal heart through cine-loop acquisition during routine screening may provide significant advantages compared with the interpretation of static images only.

Proposed Research for this Thesis
The objective of my research is to increase the detection of congenital heart disease during routine second trimester obstetrical screening. The proposed research will include three projects;

- to develop an optimal real-time image acquisition and assessment technique;
- to test the rate at which the optimal real-time image acquisition and assessment technique can be leveraged to detect CHD;
to design an online learning tool which will translate the image acquisition and assessment technique to clinical practice.

The first project will compare and evaluate the efficacy of two different real-time approaches relative to the current method using static images only. The second project will measure the rate at which CHD is detected using the real-time technique selected in project one compared with the current method using static images only. Finally, a third project will develop an online training tool for teaching sonographers and interpreting physicians to use a standardized assessment tool. A quasi-experimental study was completed to evaluate the sonographers and interpreting physicians' ability to use the online tool to learn a standardized assessment protocol.

**Project One**

The first project will identify the optimal imaging protocol for the routine assessment of the fetal heart during obstetrical screening taking into account the limitations of time and technology imposed on the sonographer during routine second trimester screening. The proposed technique will increase the amount and quality of diagnostic image information by acquiring and storing real-time cine-loop sweeps, four-seconds in length using a minimum of 30 frames/second of the fetal heart. This project is entitled, “Comparison of static, real-time and real-time, colour Doppler imaging techniques applied to the assessment of the fetal heart in routine screening”. This study will determine the optimal cine-loop
sweep imaging technique by comparing the performance of the conventional static images against two different approaches. The first will employ grey scale imaging only and the second will include colour Doppler imaging. The grey scale technique will use two cine-loop sweeps through the fetal heart beginning in the transverse plane with the fetal stomach visible. The first sweep will provide the interpreting physician with an opportunity to observe the relationship of the fetal heart with the stomach, liver and abdominal vessels in the upper abdomen. Since the first sweep will be completed at the four chamber view and the second sweep will begin at the four chamber view there will be some overlap in visualizing the morphology of the cardiac chambers. The outflow tracts will be the primary focus of the second sweep and this cine-loop sweep will expose the anatomical relationship between each outflow tract and its respective ventricle as well as the critically important cross-over of the outflow tracts. The second approach will apply the same imaging protocol as the first with the addition of a colour Doppler map overlaying the grey scale and a third colour cine-loop of the three vessel view. In order to provide a more standardized review process, interpreting physicians will be provided an anatomic checklist to guide and record decision making. The research design assumes the ultrasound systems that are used are capable of Colour Doppler processing and are configured to store or transmit real-time loops to a network.
**Research hypothesis:**

Assessment of the fetal heart in routine screening will demonstrate increased visualization of normal fetal cardiac anatomy by acquiring cine-loop sweeps using either a grey scale, (protocol B) or colour Doppler technique, (protocol C) compared with using static images, (protocol A).

**Research Aims**

- Demonstrate the ability to acquire the experimental protocols, B and C in less than five minutes
- Demonstrate an increased rate of detection of cardiac structures using real-time and real-time colour Doppler loops compared with static images
- Establish the presence of antegrade flow between the atria and ventricles
- Confirm the presence of forward flow in the AV valves, aorta and pulmonary trunk

It is anticipated that the real-time cine-loop sweeps will add considerable diagnostic value to the screening process since there will be two interpretations performed on every exam, the preliminary review by the examiner and the summary review by the interpreting physician. In addition using the real-time loops will allow the interpreting physician the opportunity to review the images repeatedly in real-time and evaluate structure at different points during the cardiac cycle. The ability to assess structure during the
diastolic phase has been found by Chaoui et al to be helpful in detecting atrioventricular septal defects (Chaoui, 2003). Further, it is well established that observation of moving structures provides a more sensitive means of detecting small differences in form (Ivry & Cohen, 1992). A cine loop of a sweep through the cardiac outflow tracts will allow the interpreting physician to better appreciate the relationship between the LVOT and RVOT which is crucial for ruling out outflow discrepancies and conotruncal abnormalities. The advantages of using three basic Doppler planes have been well documented by Chaoui (Chaoui & McEwing, 2003). Adding these Doppler images aids in the identification of outflow discrepancies, conotruncal abnormalities, valvular insufficiency and may reveal more subtle lesions such as ventricular septal defects (Chaoui & McEwing, 2003).

**Project Two**

The second project is entitled, “Increasing the Detection Rate of Congenital Heart Disease during Routine Obstetrical Screening using Two Cine-Loop Sweeps”. The goal of this study will be to demonstrate an improved detection rate of congenital heart defects using the technique identified in the first project.

**Research hypothesis:**

Using two cine-loop sweeps will increase the detection rate of congenital heart disease compared with the acquisition and review of three static images, the conventional technique.
Research Aims:

- Demonstrate increased detection of CHD
- Complete the review and interpretation of cine-loop sweeps in an equivalent period of time or less than the static images
- Maintain an equivalent or lesser rate of false positive identification of CHD using real-time cine-loop sweeps compared with static images
- Maintain an equivalent or lesser rate of indeterminate cases using cine-loop sweeps compared with static images

Project Three

The third project is entitled, “Increasing Recognition of Fetal Heart Anatomy using Online Tutorials and Mastery Learning compared with Classroom Instructional Methods”. The objective of the proposed research is to determine if the standardized assessment of the fetal heart in real-time method is a more effective tool to be used by students when learning how to identify congenital heart disease. Using a randomized, two group, quasi-experimental design, we will address the hypothesis: "Training students to use a simulation based standardized assessment technique online compared with traditional classroom instruction will increase their ability to identify congenital heart disease and increase their confidence and knowledge in assessment of the fetal heart."

Research Aims:

- Increased ability to identify normal fetal cardiac structures.
- Increased ability to identify abnormal fetal cardiac structures.
➢ Increased ability to identify abnormal cases.

The first two projects will identify a new standardized acquisition and assessment technique for evaluating the fetal heart and demonstrate that the technique is superior to the current methods of evaluating the fetal heart. A third project will devise an online learning tool that will be used to translate the new technique to clinical practice.
Chapter 3 Assessment of the Fetal Heart during Routine Obstetrical Screening, a Standardized Method

Introduction
The majority of deaths from congenital defects in childhood can be attributed to congenital heart disease (CHD). CHD is six times more common than chromosomal abnormalities and four times more common than neural tube defects (Carvalho, Mavrides, Shinebourne, Campbell, & Thilaganathan, 2002). The most common cause of birth defects, CHD is most frequently reported with an incidence of 0.8% of all live births (Hoffman & Kaplan, 2002). Improvements based on technical advances in the management and therapy of CHD has resulted in a shifting of the outcomes such that adults living with CHD outnumber the number of children with CHD (Hoffman, Kaplan, & Liberthson, 2004).

Typically the role of the sonographer during routine obstetrical screening is to identify normal and abnormal features of the fetal heart and provide morphologic images of these for the interpreting physician. The routine second trimester examination is typically performed in real-time and documented as a series of static images archived electronically or on film. Interpretation of the cardiac images is then made by a radiologist or obstetrician using the static images. Present detection rates for CHD may vary widely depending on a number of factors: gestational age, imaging centre protocol, operator skills, maternal obesity, fetal position, image acquisition protocol and the nature of the CHD (Chaoui, 2003). In order to clarify the recommended fetal heart structures for
examination the American College of Radiology (ACR), the
American College of Obstetrics and Gynecology and the
International Society of Ultrasound in Obstetrics & Gynecology
(ISUOG) have published guidelines for routine second trimester
obstetric screening (American Institute of Ultrasound in Medicine,
2013; Reddy et al., 2014). Both of these publications require the
four chamber view, also known as, a basic assessment, views of
the left ventricular outflow tract (LVOT) and right ventricular outflow
tracts (RVOT) commonly referred to as an extended examination
(ACR Guidelines and Standards Committee, American Institute of
Ultrasound in Medicine, 2003; Lee et al., 2008). Prenatal detection
rates using these methods are summarized in Table 3-1.
### Table 3-1

Prenatal Screening Detection Rate by protocol and population.

<table>
<thead>
<tr>
<th>Author Year</th>
<th>Study Design</th>
<th>Protocol</th>
<th>Subjects (n)</th>
<th>Detection (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friedberg et al., 2009</td>
<td>Prospective, multicenter, major defects only</td>
<td>Basic and extended views</td>
<td>309, low risk</td>
<td>98, (36)</td>
</tr>
<tr>
<td>Tegnander et al., 2006</td>
<td>Prospective, single site</td>
<td>Basic and extended views</td>
<td>29,460, unselected</td>
<td>55, (57)</td>
</tr>
<tr>
<td>Ogge et al., 2006</td>
<td>Prospective, multicenter</td>
<td>Basic and extended views</td>
<td>6368, unselected</td>
<td>38, (65)</td>
</tr>
<tr>
<td>Todros et al., 1997</td>
<td>Prospective, multicenter</td>
<td>Basic only</td>
<td>8299, low risk</td>
<td>6, (15)</td>
</tr>
<tr>
<td>Buskens et al., 1996</td>
<td>Prospective, multicenter</td>
<td>Basic only</td>
<td>5319, low risk</td>
<td>7, (16.7)</td>
</tr>
<tr>
<td>Stumpflen et al., 1996</td>
<td>Prospective, single center (tertiary)</td>
<td>Basic and extended views</td>
<td>3085, unselected</td>
<td>46, (85.5)</td>
</tr>
<tr>
<td>Ott et al., 1995</td>
<td>Prospective single center</td>
<td>Basic and LVOT</td>
<td>1136, low risk</td>
<td>2 (14.3)</td>
</tr>
<tr>
<td>Rustico et al., 1995</td>
<td>Prospective single center</td>
<td>Basic and extended views</td>
<td>3079, low risk, experts</td>
<td>14, (45.2)</td>
</tr>
<tr>
<td>Tegnander 1995</td>
<td>Prospective single center (tertiary)</td>
<td>Basic only</td>
<td>3945, low risk, non-experts</td>
<td>9, (26.5)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>7459, low risk</td>
<td>26, (39)</td>
</tr>
</tbody>
</table>

The range of detection varies widely by author, equipment improvements, fetal age and study type. Those studies that relied solely on the basic protocol ranged in detection from 15-39% while
those that included the extended protocol demonstrated a higher rate of detection 26.5-86.5%. It is widely accepted that the extended examination will improve the detection rate of CHD compared with the basic examination only (Eik-Nes, 2006; Michelfelder & Cnota, 2009; Tegnander, Williams, Johansen, Blaas, & Eik-Nes, 2006). Despite the inclusion of outflow tracts as part of an extended examination of the fetal heart, only two of the six studies listed in Table 3-1 achieved a detection rate greater than 60% (Oggè, Gaglioti, Maccanti, Faggiano, & Todros, 2006; Stumpflen, Stumpflen, Wimmer, 1996). There remains considerable room for improvement in detection rates, especially considering the impact of missed congenital heart disease during prenatal screening.

**Standardized Assessment**

Congenital heart disease is based on structural and functional deviations from normal embryological development. Screening the fetal heart, unlike other fetal organs, requires an evaluation of dynamic normalcy in functional terms as it beats and to assess the synchrony of the valves, chambers and conduction system. Further an enhanced exam of the fetal heart utilizing the relationship of the ventricles to the outflow tracts, the outflow tracts with respect to one another crossing at approximately 70 degrees and clarify the function of other important structures such as the cardiac valves (Allan, 2003). A thorough assessment of the continuity of these structures and their function is not feasible as a series of static images.
Current practices in routine obstetrical screening are limited in a number of important ways. Limited screening time is a significant constraint and the design of a standardized method to detect CHD that enables adoption by sonographers and interpreting physicians must take this into account. The practice guidelines provided by the American Institute of Ultrasound in Medicine and the American College of Radiology clearly articulate what fetal cardiac structures should be imaged, however, they do not specify how or to what standard they should be documented (American Institute of Ultrasound in Medicine, 2013). For example the guidelines do not specify that the interpreting physician interpret a real-time assessment of the fetal heart, nor do they establish any specific relationships that must be observed such as that of the outflow tracts relative to one another and their continuity with the ventricles. The interpretation of the practice guidelines could lead to a less than optimum screening of CHD.

A number of authors have identified the use of cine-loops as a practical means of improving the assessment of the fetal heart (Mcgahan et al., 2007; Poole et al., 2013; Scott et al., 2008; Sklansky, 2007). Acquiring cine-loops as compared to static images certainly has the potential to increase the visualization rate of normal fetal heart structures.(Scott et al., 2008) A standardized assessment can be performed if the image acquisition process is well structured and includes cine-loops.
Image Acquisition

Figure 3-1
The first cine-loop sweep begins at the level of the stomach in the transverse plane sweeping into the four chamber view of the fetal heart. The second cine-loop sweep begins at the level of the four chamber heart indicated by the dotted arrow and continues through the outflow tracts. Line drawings provided by Ken K. Wong, Graphic Designer, Mohawk College.

A real-time assessment of the fetal heart can be completed using two sweeps and storing them as cine-loops, see Figure 3-1. The situs to four chamber sweep begins in the transverse abdominal plane at the level of the stomach and ends at the four-chamber view. The four-chamber to outflows sweep begins in the four chamber view and slides through the ventricular outflow tracts. Together these two sweeps will provide the examiner and the
interpreting physician with a more complete set of images in real-time for assessment compared with static images.

Sonographic system settings should ensure that the fetal thorax fills 50-75% of the field of view, see Figure 3-2. The focus and frequency settings, including tissue harmonic processing should be optimized. Frame rate should be set between 30-100 Hz, with a minimum threshold of 30Hz (Fredouille, 2007). Cine-loops can be stored as DICOM files in either a MiniPACS or Radiology PACS application. Sharing cine-loops with experts can be accomplished within an enterprise application or as an exported video file, formatted as an AVI, MPEG, Quick Time or similar standard. Typical video file sizes for a four-second, grey scale cine-loop as a Quick Time and MPEG movie files range from 1-2 megabytes, while AVI files can be much larger in size, 40-50 megabytes. Given the storage capacity available as a local server, enterprise server or cloud storage solution, cine-loops do not impose a burden on the storage capacity for most PACS applications.
**Figure 3-2**
The fetal thorax fills more than 50% of the field of view, transducer frequency and focus are optimized for spatial resolution. The tissue harmonic signal processing option is selected and the frame rate is set at 51 Hz.

**Figure 3-3**
Static images representing key landmarks demonstrate normal situs with both stomach and cardiac apex on the left beginning with the situs-four chamber cine-loop sweep in A-B. Line drawings provided by Ken K. Wong, Graphic Designer, Mohawk College.
To acquire the situs to four-chamber sweep, position the transducer in a transverse plane at the level of the stomach, slide the transducer cephalad from the abdominal circumference into the four chamber view, without changing angles to the fetus. The stomach and fetal heart should be visible on the left side of the fetus. A good four chamber level will include one complete rib (Fredouille, 2007). Acquisition of the cine-sweep should begin showing situs, and capture at least 2 beats of the situs in order to allow the viewer to be able to appreciate the pulsatility of the aorta. Next, slowly slide the transducer cephalad without changing the angle, see Figure 3-3. The Inferior Vena Cava (IVC) should be shown to enter into the right atrium as the four chamber view approaches. The acquisition should end with at least two beats of the four chambers visible. Practice may be required to obtain a complete sweep. It is a good practice to acquire several sweeps and keep the best one. From the four chamber view, rotate slightly toward fetal left shoulder and angled cephalad, see Figure 3-4. The first outflow tract visible is the left ventricular outflow tract, see Figure 3-5. Angling the transducer more cephalad will enable visualization of the right ventricular outflow tract (Drose, 2013) The pulmonary artery is the most anterior structure in the heart so often the bulk of the heart is not visible at this level. The importance of the relationships between these structures is depicted in Figure 3-4. In this example, a form of transposition of the great vessels is identified by the abnormally parallel course of the outflow tracts.
The blood flows out of the right ventricle through the LVOT while blood flow leaving the left ventricle passes through the RVOT. The parallel configuration of the outflow tracts associated with the transposition spectrum of CHD is defined.

Image provided by Judy Jones, London Health Sciences. Line drawings provided by Ken K. Wong, Graphic Designer, Mohawk College.

Assessment
Before an assessment of the fetal heart is made, it is important to determine the fetal lie in order to enable identification of fetal left and right anatomy. Once this is determined a five step assessment can be undertaken to determine normalcy, see Table 3-2.

Step 1
Assess the situs, axis and size of the fetal heart. In a transverse section through the fetal abdomen, identify the unilateral organs, see Figure 3-3;

a. Toward the left a descending aorta and stomach; aorta is circular and can be identified by its pulsations corresponding to the fetal heart rate.

b. A right sided IVC, slightly anterior and to the right of the aorta; IVC is circular/oval in shape, is not pulsatile but is
collapsible, and it may be seen to change size over the cardiac cycle in response to changes in cardiac pressures. The size can also be influenced by pressure exerted by surrounding organs. Careful inspection is required to locate this vessel since it may be difficult to see due to its small size. The IVC should be seen to enter the RA when performing the situs sweep.

Use the spine as a guide to the centre of body; an imaginary line can be drawn from spine to anterior abdominal wall to form the antero-posterior axis; this axis divides the transverse section into left and right halves.

There are three types of cardiac Situs that can be identified, Situs Solitus, Situs Inversus and Situs Ambiguous. Situs Solitus represents the normal arrangement as described above. Situs Inversus represents the complete inverse of normal anatomy, it is very important that the fetal left and right is identified to confirm this condition. There are two common forms of Situs Ambiguous, right atrial isomerism also known as asplenia and left atrial isomerism also known as polysplenia. When the aorta and IVC are found on the same side of the body, the arrangement is referred to right atrial isomerism, the liver is usually midline and the stomach can be found on either side of the body. Left atrial isomerism occurs when the IVC is absent in the abdomen and replaced by an azygous vein which runs parallel to the aorta and slightly posterior on either the left or right side.
The transverse cine sweep provides the examiner with the opportunity to assess the cardiac axis, stomach and heart relationship. The cardiac axis can be defined as levocardia, mesocardia or dextrocardia. Levocardia is the normal position of the heart in the left chest with the apex of the heart leftward and the interventricular septum forming a 45 degree angle relative to the anterior-posterior axis of the chest. A heart positioned centrally in the chest is referred to as mesocardia. Dextrocardia is a condition where the heart is found in the right chest. Dextrocardia can be defined by three types; 1) dextroversion, where the apex is rightward, 2) dextroposition, usually due to a space occupying lesion, apex remaining leftward and 3) mirror image dextrocardia, the heart is completely inverted in the right chest.

Step 2

It will be possible to assess the four chambers in real-time using both sweeps. See Figure 3-3. Two atria should be visualized approximately equal in size and separated by an atrial septum, the foramen ovale comprises approximately one half of the septum primum moving into and back from the left atrium, this septum primum forming the superior aspect of the crux of the heart. The left atrium is located anterior to the descending aorta and spine. The descending aorta should be the only vessel (seen as a pulsatile circle) between the left atrium and the spine. In over 50% of normal studies, at least 2 of the 4 pulmonary veins will be seen, usually one from each lung (Antebay, E Y, Shimonovitz, S., Yagel, 1994; Scott et
al., 2008). Two ventricles should be seen, approximately the same size, with symmetry in wall thickness and contractility. The right ventricle will become slightly larger than the left ventricle as pregnancy progresses. The ventricles will be divided by a complete interventricular septum, tricuspid and mitral valves should be about the same size and open freely, and the tricuspid valve is inserted slightly closer to the apex than the mitral valve. This offset is best seen when the apex is facing toward or away from the transducer, due to a specular reflection of the sound against the perpendicular valves. Identification of this feature is significant as the tricuspid valve is always attached to the RV and the mitral valve is always attached to the LV. The left ventricle will be conical in shape, and its walls will be relatively smooth. The right ventricle is closest to the anterior chest wall, pyramidal in shape and its walls will be rougher due to the presence of trabeculae. The apex of the right ventricle may appear more “filled in” compared to the apex of the left ventricle due to the presence of the moderator band.

**Step 3**
The four-chamber to outflows sweep will expose the outflow tracts and their origin relative to their respective ventricles. See Figure 3-5. In this step, the Left Ventricular Outflow Tract (LVOT) will be assessed to confirm that the aorta is seen arising from the left ventricle. The inter-ventricular septum should continue as an uninterrupted wall and continuous with the anterior aortic root wall. The base of the anterior mitral valve should be in close proximity to the point where the posterior aortic root begins and the aortic valve
leaflets should be thin and open well, appearing to disappear in systole.

**Step 4**
In this step, the normal position of the Right Ventricular Outflow Tract (RVOT) will be confirmed. The RVOT should be seen anterior to the LVOT, the pulmonary artery is seen arising from the right ventricle. The pulmonary artery and the aorta cross at their origins, further downstream they do run parallel for a short distance. The pulmonary artery trifurcates into the ductus arteriosus and two smaller arteries, the right and left branches. The pulmonary valve leaflets are thin and open well, appearing to disappear in systole.

**Step Five**
This step will confirm that the outflow tracts intersect at their origins at approximately 70 degrees. For example, the presence of a parallel orientation of the outflow tracts indicates an abnormal fetal heart. The pulmonary artery is slightly larger than the aorta; this becomes more evident later in gestation. The cine-loop will provide the opportunity to review the frames repeatedly to ensure that the orientation of the outflow tracts is normal.
Figure 3-5

The four chamber to cephalically angled outflow tracts sweep represented by 5A-5B. It is often possible to include the three vessel view in this sweep. Line drawings provided by Ken K. Wong, Graphic Designer, Mohawk College.

Summary

Assessment of the fetal heart during routine obstetrical screening is an important element of the examination. In practice the detection of CHD remains comparatively low relative to the detection of pathology in other anatomical systems (Grandjean et al., 1999; Tegnander et al., 2006). The implementation of a standardized assessment technique of the fetal heart in real-time, using cine-loop sweeps represents a practical approach that can be used by the
majority of screening centres (Scott et al. 2013). The standardized technique is limited to those centres with the capability of storing cine-loops as part of the clinical record. The basic obstetric examiner must also become familiar with acquiring cine-loops in a systematic way ensuring that the cine-loop sweep start and end-points are observed enhancing the benefits of an extended examination in real-time. However if these constraints can be overcome, the benefits of a real-time assessment and an extended examination can be fully realized.
Chapter 4 Increasing the Detection Rate of Normal Fetal Cardiac Structures: A Real-Time Approach

Introduction
The use of ultrasound imaging for routine fetal screening in the second trimester has been adopted by the Canadian health care system and a number of European countries as a standard of care (Rumack, Wilson, Charboneau, 2005). According to a survey of 2758 referrals to the fetal cardiology unit at Guy’s Hospital, London, UK, 80% of congenital heart defects emerge from women at low risk for congenital heart defects (Sharland, 2004). This fact underscores the importance of routine screening for detection of these defects. Routine screening provides a more accurate measure of gestational age, earlier detection of multiple pregnancies and may detect congenital malformations. The Eurofetus study identified marked differences in sensitivity for detection of different malformations. Abnormalities of the urinary system and nervous system were most easily detected with a sensitivity of 88.5% and 88.3% respectively (Grandjean et al., 1999). In this study cardiac abnormalities were not well detected; sensitivity for major cardiac defects was 38.8% and minor defects 20.8% (Grandjean et al., 1999). In Canada, an obstetric screening examination is performed in real-time and documented as a series of static images archived electronically or on film. The interpretation of the cardiac images is performed by a Radiologist or Obstetrician using the static images. Present detection rates for congenital heart defects (CHD) vary widely depending on a number of factors: operator skills, maternal obesity, fetal position, inadequate image
optimization, gestational age and visualization of the four chamber view only (Sharland, 2004). The American College of Radiology (ACR) and the International Society of Ultrasound in Obstetrics & Gynecology (ISUOG) have published guidelines for routine second trimester screening that require the four chamber view and views of the left ventricular outflow tract (LVOT) and right ventricular outflow tract (RVOT) to address this limitation (American Institute of Ultrasound in Medicine, 2013). Acquisition of static images of the fetal heart provides a very limited quantity of diagnostic information, in that the identification of normal cardiac structures cannot be completely demonstrated as a series of a few static slice images. The interpretation of key structural relationships will only be completed during a real-time interrogation. In practice, the detection of the critical normal structures is accomplished solely by the sonographer. This approach limits the interpreter’s ability to confirm the findings of the sonographer. The main objective of this pilot study is to demonstrate that acquiring real-time loops of the fetal heart can be accomplished with minimal additional acquisition time and skill. In addition, static and real-time techniques will be compared in an effort to demonstrate the additional anatomical information that is accessible using a real-time acquisition.

The real-time loops will add considerable diagnostic value to the screening process since there will be two interpretative sweeps performed on every exam: the preliminary review by the sonographer and the summary review by the sonologist. Another advantage of using the real-time loops is the opportunity it provides
the sonologist to review the images repeatedly in real-time, allowing them to evaluate structures at different points during the cardiac cycle. It is well established that observation of moving structures provides a more sensitive means of detecting small differences in form (Ivry 1992). The ability to assess structures during the diastolic phase has been found to be helpful in detecting atrial-ventricular septal defects (Chaoui, 2003). A cine-loop of a sweep through the cardiac outflow tracts will allow the sonologist to better appreciate the cardiac morphologic relationship such as the LVOT and RVOT which is crucial for ruling out conotruncal abnormalities. Hosono et al, (2002) found the use of tissue harmonic imaging (THI) to be advantageous in imaging fetal cardiac tumors due to improvements in image contrast (Hosono, Chiba, Kanai, & Kanagawa, 2002). A comparative study was performed using two techniques, conventional, 3.5 MHz frequency compared with a tissue harmonic signal of 3.6 MHz. THI was used to improve the visualization of the cardiac tumors. Using THI could improve the quality of the images and may influence the detection rate of cardiac structures as well (Paladini, Vassallo, Tartaglione, Lapadula, & Martinelli, 2004).
Table 4-1
Clinical site survey data.

<table>
<thead>
<tr>
<th>Obstetrical Exams/Day</th>
<th>Number of sites (%)</th>
<th>Routine Views</th>
<th>Number of sites (%)</th>
<th>Operating PACS (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Four Chamber</td>
<td>21 (100)</td>
<td>20 (95)</td>
</tr>
<tr>
<td>0-5</td>
<td>7 (33)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5-10</td>
<td>9 (42)</td>
<td>LVOT</td>
<td>18 (86)</td>
<td></td>
</tr>
<tr>
<td>10-15</td>
<td>2 (10)</td>
<td>RVOT</td>
<td>18 (86)</td>
<td></td>
</tr>
<tr>
<td>15-25</td>
<td>1 (5)</td>
<td>Aortic Arch (long axis)</td>
<td>7 (33)</td>
<td></td>
</tr>
<tr>
<td>25-30</td>
<td>1 (5)</td>
<td>Ductal Arch (long axis)</td>
<td>3 (14)</td>
<td></td>
</tr>
<tr>
<td>30-35</td>
<td></td>
<td>Great Vessels (short axis)</td>
<td>6 (29)</td>
<td></td>
</tr>
<tr>
<td>&gt;35</td>
<td>1 (5)</td>
<td>Septum</td>
<td>1 (5)</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>21 (100)</td>
<td></td>
<td>21 (100)</td>
<td>21 (100)</td>
</tr>
</tbody>
</table>

A survey of 21 local screening centers illustrated in Table 4-1 found that 95% of centres acquired and stored images using a Picture Archiving Communications System (PACS). Most centres acquired three static images of the fetal heart: the four chamber view, the LVOT and RVOT view. See Table 4-1. For the purpose of this pilot study, this combination of static images represents the conventional technique, protocol A.

Research Question/Objectives
This study compared static and real-time imaging techniques applied to the assessment of the fetal heart in routine screening.

RESEARCH AIMS
- Demonstrate the ability to acquire the experimental protocol B in less than five minutes
• Demonstrate an increased rate of detection of cardiac structures using real-time cine-clips compared with static images

**Method**
The research protocol was reviewed and approved for use by the ethics committee of Charles Sturt University (Wagga Wagga, NSW, Australia) and the ethics committee of Mohawk College (Hamilton, Ontario, Canada). Exclusion criteria included a family history of congenital heart defects or an abnormal second trimester obstetric sonogram. All 28 subjects had a normal second trimester sonogram prior to participation in this study. Images were acquired using the Philips HDI 5000, Envisor, Medical Systems, Bothell, WA, USA, sonography systems. Images were acquired using a curvilinear array transducer with a fetal cardiac preset using tissue harmonic image processing, with a bandwidth of 2.5-5.0 MHz.

**Table 4-2**
**Subject demographics and protocol acquisition times.**

<table>
<thead>
<tr>
<th>Subjects (n=28)</th>
<th>Average</th>
<th>95% Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gestational Age</td>
<td>27 weeks 0 days</td>
<td>24 weeks 5 days – 28 weeks 6 days</td>
</tr>
<tr>
<td>Maternal BMI</td>
<td>27.8</td>
<td>25.8-29.8</td>
</tr>
<tr>
<td>Maternal Body Wall (cm)</td>
<td>1.8</td>
<td>1.6-1.9</td>
</tr>
<tr>
<td>Acquisition Time, Protocol A (00:00)</td>
<td>3:49</td>
<td>2:39-4:58</td>
</tr>
<tr>
<td>Acquisition Time, Protocol B (00:00)</td>
<td>4:18</td>
<td>3:19-5:17</td>
</tr>
<tr>
<td>Acquisition Time, Protocol C (00:00)</td>
<td>6:32</td>
<td>5:14-7:51</td>
</tr>
</tbody>
</table>

Subjects were scanned using three different techniques: Protocol A, consisting of three images of the fetal heart including the four
chamber view, the LVOT and the RVOT view. See Figures 4-1, 4-2, and 4-3. The average acquisition time for each technique independent from the others is described in Table 4-2.

**Figure 4-1**
Static image of the four chamber view.

**Figure 4-2**
Static image of the LVOT view.
Figure 4-3
Static image of the RVOT view.

Protocol B, the real-time sweep, was comprised of two grey scale sweeps of 4 four seconds duration each through the abdomen and fetal heart. The first sweep began at the level of the transverse abdominal circumference with a visible stomach and swept into the transverse four chamber view. The second sweep began at the four chamber plane and swept through the LVOT and RVOT. See Figures 4-5, 4-6 and 4-7. Protocol C was comprised of three real-time colour cine-loops of four seconds duration. The first was a sweep from the level of the transverse abdominal circumference with a visible stomach into the transverse four chamber view. The second sweep began at the four chamber view and swept through the LVOT and RVOT. The third was a colour cine-loop of the three vessel view.
Figure 4-4
Abdominal circumference from real-time sweep #1.

Figure 4-5
Four chamber view from real-time sweep #1.
Figure 4-6
LVOT view from real-time sweep #2.

Figure 4-7
RVOT view from real-time sweep #2.

Informed consent was obtained and subjects were randomly assigned a sonographer who completed either protocol A, B or C.
A total of five sonographers acquired images for this project. All sonographers had a minimum of three years’ experience performing obstetrical sonography and were ARDMS credentialed as RDMS (obstetrics and gynecology). The sonographer recorded the scan time for the acquisition using an electronic timer. Every subject was scanned by at least two different sonographers. Images were acquired and stored on the Philips Medical Systems Xcelera Minipacs. No additional training was provided to save the real-time loops compared with the static images. Sonographers were limited to a maximum of 10 minutes to complete each separate protocol in an effort to replicate the practical limitations of the clinical environment.

The image sequences acquired were reviewed independently by two different fetal cardiac sonography experts blinded to each others’ results. The reviewers are expert in acquiring and interpreting fetal cardiac sonograms. The first was a sonographer (EX1) with 16 years pediatric cardiac experience registered with RDCS (pediatric and fetal echo) credentials and the second a Pediatric Cardiologist (EX2). In addition to the expert reviewers, two non-experts reviewed the images independently and were blinded to each others’ results. The first was a radiology resident in year three of his training (NE1) and the second was a cardiac sonographer with RDCS credentials and less than one year of experience in performing fetal cardiac studies (NE2). Each reviewer recorded the detection of five cardiac structures listed in table 3 as: detected = 1 or, missed = 0. A complete normal assessment
required a score of 5, an incomplete assessment is recorded as any total less than 5.

**Statistical Analysis**

Inter-observer differences were tested using a Kappa score for agreement between detection of structures. A one-way ANOVA was performed to test for agreement between the means of total detection rate scores and the means of the acquisition times. Detection rate differences for complete and incomplete assessments were analyzed using the McNemar Chi-square test.

**Results**

The subjects’ average gestational age was 27 weeks 0 days, with an average BMI = 27.8 and an average body wall thickness = 1.8 cm, see Table 4-2. The acquisition time for the static images, Protocol A, is statistically equivalent to the acquisition time for Protocol B. The mean time for both is less than 5 minutes. See Table 4-2. The acquisition of protocol C exceeded 5 minutes with a mean time of 6:32, statistically different than protocols A and B. Using Kappa scores the inter-observer agreement between experts for detection of cardiac structures using static images were found to be equal to 0.19, +/- 0.09, 95% confidence interval for the four chamber view, 0.14, +/- 0.10, 95% confidence interval for the LVOT view, 0.16, +/- 0.10, 95% confidence interval for the RVOT view and 0.20, +/- 0.12, 95% confidence interval for the Cross over view. The inter-observer agreement between non-experts for detection of cardiac structures using static images were found to be equal to 0.45, +/- 0.12, 95 confidence interval for the four chamber view,
0.42 +/- 0.11. 95% confidence interval for the LVOT view, 0.45 +/- 0.12, 95% confidence interval for the RVOT view and 0.49 +/- 0.13, 95% confidence interval for the Cross over view. The inter-observer agreement between experts for detection of cardiac structures using Kappa scores for the real-time images were found to be, 1.0 +/- 0.10, 95% confidence interval for the four chamber view, 0.19, +/- 0.09, 95% confidence interval for the LVOT view, 0.21, +/- 0.10, 95% confidence interval for the RVOT view and 0.18, +/- 0.12, 95% confidence interval for the Cross over view. The inter-observer agreement between non-experts for the real-time images were found to be, 0.19, +/- 0.09, 95% confidence interval for the four chamber view, 0.14, +/- 0.10, 95% confidence interval for the LVOT view, 0.16, +/- 0.10, 95% confidence interval for the RVOT view and 0.20, +/- 0.12, 95% confidence interval for the Cross over view.

**Table 4-3**

Rate of detection of cardiac structures by technique.

<table>
<thead>
<tr>
<th>Expert n=28</th>
<th>Four Chamber (%)</th>
<th>LVOT (%)</th>
<th>RVOT (%)</th>
<th>RVOT Cross over LVOT (%)</th>
<th>Axis and Size (%)</th>
<th>Complete Exam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static</td>
<td>68</td>
<td>64</td>
<td>64</td>
<td>47</td>
<td>93</td>
<td>29</td>
</tr>
<tr>
<td>Colour Doppler Loops</td>
<td>84</td>
<td>82</td>
<td>79</td>
<td>73</td>
<td>93</td>
<td>39</td>
</tr>
<tr>
<td>Grey Scale Loops</td>
<td>100</td>
<td>86</td>
<td>81</td>
<td>73</td>
<td>100</td>
<td>71</td>
</tr>
</tbody>
</table>

The real-time image loops were found to have the highest detection rates for all anatomic structures compared with the static images and colour loops, see Table 4-3. The four chamber view was
identified in 100% of all real-time loops and in only 68% of static images, and 84% of colour loops. The LVOT and RVOT cross-over was detected in 73% of real-time loops and only 47% of static images. Similar differences were found for the LVOT and RVOT as individual structures.

Assessing the static images, 39% of studies generated a score of 5 for complete assessment compared with the real-time technique that was able to completely assess the normal structures in 71% of studies. This generated a statistically significant difference between proportions = 0.321, $p=0.0352$ using the McNemar Chi-square test.

The colour Doppler loops provided a complete assessment in only 39% of cases. The colour Doppler loops did provide the ability to assess the blood flow through the atrial-ventricular valves and semilunar valves in the majority of cases and this represents additional diagnostic information compared with the grey scale static and real-time loops. The colour Doppler loops were able to assess the four chamber view and five chamber view in the majority of cases. The 3 vessel view was only achieved in 45% of cases, see Table 4-4.

**Table 4-4**

**Detection rate of colour flow using colour Doppler loops by view.**

<table>
<thead>
<tr>
<th>Expert n=28</th>
<th>Four Chamber (%)</th>
<th>Five Chamber (%)</th>
<th>Three Vessel View (%)</th>
<th>Assessment of Valves for Regurgitation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colour Doppler Loops</td>
<td>91</td>
<td>84</td>
<td>45</td>
<td>86</td>
</tr>
</tbody>
</table>
Table 4-5
Detection rate differences between experts and non-experts.

<table>
<thead>
<tr>
<th>Expert/Non-expert Difference</th>
<th>Four Chamber (%)</th>
<th>LVO T (%)</th>
<th>RVOT (%)</th>
<th>RVOT Crossover LVOT (%)</th>
<th>Axis and Size (%)</th>
<th>Complete Exam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static</td>
<td>0</td>
<td>13</td>
<td>4</td>
<td>8</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>Colour Doppler Loops</td>
<td>11</td>
<td>4</td>
<td>0</td>
<td>7</td>
<td>2</td>
<td>28</td>
</tr>
<tr>
<td>Grey Scale Loops</td>
<td>14</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>2</td>
<td>15</td>
</tr>
</tbody>
</table>

The expert reviewers and non-expert reviewers were found to agree closely in their assessment of static images. The largest difference between these groups was in evaluation of the LVOT with a difference of 13% between groups, see Table 4-5. All other structures differed by less than 10% respectively. There was close agreement between the experts and non-experts interpreting the grey scale and colour loops with the exception of the four chamber view where the grey scale loop differed by 14% and the colour loop differed by 11%. Assessment of a complete exam was in close agreement between experts and non-experts for the static images with a greater difference of 15% and 28% demonstrated in Table 4-5, with the grey scale and colour loops respectively.

Sample Images
The static image of the four chamber view allows the observer to distinguish the axis, size and left/right chambers under ideal conditions, see Figure 4-1. The static images of the LVOT and RVOT, see Figures 4-2 and 4-3, demonstrate continuity between
each outflow tract and the corresponding chamber. The static images cannot effectively assess the cardiac valves or cardiac motion, except by comparative images in diastole versus systole. Even then, contractility and valve excursion can only be captured on real-time cine-loops.

Figure 4-8
Pulmonary veins from real-time sweep #2.

Figure 4-9
Four chamber view with colour Doppler from sweep #1.
**Figure 4-10**
Five chamber view with colour Doppler sweep #2.

**Figure 4-11**
Three vessel view from colour Doppler cine-loop #3.
For the sake of this thesis, static images have been extracted from the real-time loops in an attempt to demonstrate the added value loops provide. The first sweep sample begins at the transverse abdominal circumference, see Figure 4-4. The four chamber view is visualized in Figure 4-5. The second sweep demonstrates the LVOT in Figure 4-6 and the RVOT is visualized in Figure 4-7. In addition, the real-time sweeps provided continuity between the stomach and abdominal circumference in 100% of real-time studies. One or more pulmonary veins were visualized as contiguous structures entering the left atrium in 56% of real-time cases compared with 3.6% of cases with static images, see Figure 4-8. A colour image extracted from a sweep from the abdominal circumference to the four chamber view demonstrated blood flow through the atrial-ventricular valves in Figure 4-9. The blood flow through the LVOT is evident as an image acquired during the sweep, from the four chamber through the outflow tracts, see Figure 4-10. In Figure 4-11 the great vessels demonstrate antegrade blood flow in a three vessel view. If adequately seen, the three vessel view can eliminate the need for ascending aorta and ductal arch views (L Allan, 2004)

Discussion
The subjects were a representative sample of expectant mothers in the late second trimester and early third trimester between 24 weeks, five days and 28 weeks, six days. The requirement of a previous normal diagnostic second trimester sonogram result, as a prerequisite for participation in this study, resulted in the mean
gestational age of 27 weeks 0 days. The grey scale, real-time sweeps, mean acquisition time (4:18) were acquired quickly like the static images, mean acquisition time (3:49), and very little additional expertise was required to capture the real-time loops.

The structure of the heart is complex due to relationships between structures, such as the crossover of the outflow tracts, which is critical for determining normalcy. Three static views of the four chamber and outflow tracts are inadequate for complete assessment in the majority of cases. Static images are much less likely to be able to demonstrate subtle anatomic structures, such as the moderator band, atrio-ventricular valve offset, that are useful for distinguishing the left and right chambers. Static images cannot assess the valves and their motion effectively, and this limits observer confidence in detecting outflow function and their surrounding morphologic relationships. The real-time loops are able to detect these subtle anatomic structures and their motion; this fact is reflected in the ability of the real-time loops to detect a completely normal heart in 71% of studies compared with 39% of static studies.

In addition to the identification of the four chamber and outflow tracts, the real-time sweeps provided the continuity of the left sided stomach in the abdomen, as the sweep translates from the abdomen to the chest in 100% of cases.

In a few cases, the relationship between the outflow tracts could not be established in static images or real-time at normal speed; however, use of a frame by frame analysis established that relationship. This affirms the value of acquiring loops of information,
rather than individual slices as well as the need to re-evaluate the heart in real-time after the image acquisition process.

The colour Doppler loops provided useful blood flow information in most cases but this advantage was limited to some degree by the fact that colour blooming had the effect of obscuring part of the anatomy represented in grey scale. Unfortunately, our PACS and ultrasound systems did not permit the suppression of colour. Another drawback to the colour Doppler was the need for additional operator expertise to fine tune the colour velocity scale or pulse repetition frequency (PRF) and colour gain. The three vessel view was detected in only 45% of cases compared with 91% and 84% for the four chamber and five chamber views. This difference most likely reflects the relative difficulty in acquiring the three vessel view compared with the four chamber and five chamber views.

It is interesting to note that in nearly all cases there were only minor differences in the detection rates between the expert image reviewers and non-expert reviewers. Review of the static images resulted in the least difference between these groups, likely due to the fact that reviewers assessed only one image/view in comparison with the real-time loops that generated a series of 120 images from a four second acquisition. The cine-loops provided the reviewers with so much additional information it had the effect of introducing a wider range of interpretation. Based on these findings, it is clear that the identification of the four chambers, outflow tracts, outflow tract cross over, size, situs, and position can be achieved consistently by experts and non-experts.
Real-Time Methodology

Typically second trimester screening exams are scheduled for approximately 30 minutes in which time the sonographer is obliged to interrogate the maternal pelvic and fetal anatomy, as well as acquire representative images and measurements to estimate gestational age. Fetal cardiac anatomy, owing to its complex shape and rapid movement, represents the sonographer’s greatest diagnostic challenge. Given these constraints, a robust screening technique needs to be able to provide the maximum relevant anatomical information with the minimum operator skill and time. For most screening centers a reasonable goal would be to identify an abnormal heart and refer the patient to a pediatric cardiology laboratory to diagnose the specific nature of the defect based on a standardized assessment. The use of colour Doppler cine-loops provided additional blood flow information in the majority of cases but this advantage was off-set by the additional time required to acquire these loops. Additional operator skill is needed to apply colour Doppler effectively and colour blooming may obscure visualization of some grey scale anatomy unless it is suppressed. For these reasons it is proposed that the two sweep cine-loop acquisition technique tested in this study be used for assessing the fetal heart in the second trimester. Applying this method of acquisition will allow the image interpreter to identify the key cardiac anatomical landmarks and relationships that were assessed in this study in the majority of cases. This method will provide the most effective assessment of fetal cardiac anatomy with minimal additional time and skill.
**Study Limitations**

It was not possible to blind the observer to the techniques used for acquisition, since a static image is inherently different to a real-time loop. The manipulation of the real-time loops as a frame by frame analysis was left to the discretion of the individual reviewers. While this may have limited the standardization of the image presentation the manipulation of frame rate by the user is a key advantage of the technique.

**Conclusion**

Real-time sweeps through the fetal heart are easily and rapidly acquired with minimal additional operator skill. Acquiring four-second, real-time loops provides the sonologist with enhanced information to more effectively assess the fetal heart. This study was able to demonstrate a complete cardiac assessment in 71% of studies using a real-time acquisition technique compared with 39% of static image acquisitions. The use of colour Doppler provided blood flow information of the atrial-ventricular valves in 86% of subjects but was not compared to static colour images. A standardized two sweep acquisition through the fetal heart can be acquired quickly and with minimal additional operator skill. In the future, studies comparing the performance of this technique between normal and abnormal fetal hearts will be needed to demonstrate the clinical value of real-time loops for detecting congenital heart disease.
Chapter 5 Increasing the Detection Rate of Congenital Heart Disease during Routine Obstetrical Screening Using Two Cine-Loop Sweeps

The majority of deaths from congenital defects in childhood can be attributed to congenital heart disease (CHD) (Lindsey Allan, 2010; Carvalho et al., 2002). The most common cause of birth defects, CHD is most frequently reported with an incidence of 0.8% of all live births (Gilboa, Salemi, Nembhard, Fixler, & Correa, 2010; Hoffman & Kaplan, 2002). The prenatal diagnosis of congenital heart disease can improve clinical outcomes of those affected after birth (Bull, 1999; Hornberger, 2008; Jaeggi et al., 2001; Yates, 2004). Prenatal diagnosis of congenital heart disease is critically important to ensure optimal management of the pregnancy, optimal delivery of the baby and provision of support for parental decision making. In addition, those at high risk for CHD may be relieved of additional anxiety and fears due to possible CHD by confirmation of normality (Kitchiner, 2004).

Prenatal screening performance has been documented in the literature extensively over the past 25 years and although the reports vary in study design, they consistently demonstrate poor performance in the low risk population using a four chamber assessment with detection rates ranging from 5% to 48% (Achiron, Glaser, Gelernter, Hegesh, 1992; Buskens, Grobbee, 1996; Friedberg et al., 2009; Oggè et al., 2006; Tegnander, Eik-Nes, Johanesen, 1995). More recently, a number of prospective studies that included the outflow tracts and substantial additional operator
training, found that some improvements were observed with sensitivities ranging from 57% to 78% (Achiron, Glaser, Gelernter, Hegesh, 1992; Carvalho et al., 2002; Tegnander et al., 2006).

While the inclusion of outflow tracts as an extension to a basic exam of the four chambers has provided encouraging results, further improvements in screening protocols are needed. The interpretation of static images of the heart used by the majority of routine obstetric screening centres is a significant barrier to the detection of CHD (Sklansky, 2007). In some instances, identification of an atrioventricular septal defect for example, is increased by assessing the four chamber view during the diastolic and systolic phases of the cardiac cycle (Chaoui, 2003). Reliance on static images only for interpretation assumes that the sonographer will recognize CHD in the course of their real-time assessment of the fetal heart and record an image that clearly depicts the CHD. In the event that the sonographer misses the abnormality, it is unlikely that the CHD will be demonstrated on the static images since image acquisition is operator dependent. However, several instrumentation alternatives are available to interpreting physicians. Dynamic three-dimensional volume sets of the fetal heart can be stored for review and interpretation using Spatial-Temporal Image Correlation (STIC) technology, (Chaoui, 2003; Sklansky, 2007). Three-dimensional imaging has the potential to improve the detection rate of CHD since it provides unlimited opportunities to review the fetal heart as an acquired volume or as a cine-loop of real-time slices (DeVore et al., 2003). Acquisition of three-
dimensional volumes of the fetal heart requires additional training and resources (Sklansky, 2007). The need for additional investments in training and equipment is mandatory. Though three-dimensional assessment of the fetal heart has not become a standard practice in routine obstetrical screening it is well on its way to becoming the most effective tool to assess the fetal anatomy. 

The use of cine-loop sweeps to assess the fetal heart however, has been recommended as a practical means of increasing the detection rate of CHD (Sklansky, 2007). Additionally the use of cine-loop sweeps to examine the criss-cross of the outflow tracts in an effort to increase the likelihood of detecting conotruncal defects is well published (McGahan et al., 2007; Poole et al., 2013; Sklansky, 2007). No new equipment is required other than the storage capacity to store cine-loops within the imaging facility and very little additional sonographer training is needed since the sweeps can be incorporated into existing imaging protocols with little effort. Short axis cuts through the fetal heart yields morphologic information far superior to mere four-chamber and outflow tract views. Extension to the three-vessel view, though not purposefully examined on two-dimensional static imaging, will often be seen on a cine-loop sweep. The first cine-loop sweep begins at the level of the stomach in the transverse plane and moves superiorly to the four chamber view. The second sweep begins at the four chamber view in transverse and sweeps upward to include the outflow tracts. The objective of this study was to determine if using two cine-loop
sweeps would improve the detection of congenital heart disease compared with static images.

**Materials and Methods**

**Subjects**

This study was approved by the Charles Sturt University Ethics in Human Research Committee, Mohawk College research ethics board, the Hamilton Health Sciences/Faculty of Health Sciences research ethics board and the Grey Bruce Health Services research ethics board. Informed parental consent was obtained for every case. Normal images including static images and cine-loop sweeps of the fetal heart from 79 expectant mothers during the course of their routine second trimester screening sonogram were obtained. Static images and cine-loop sweeps of the fetal heart from 14 expectant mothers referred to the McMaster Children’s Hospital, pediatric cardiology laboratory for follow-up of suspected congenital heart defects were also gathered. Diagnostic accuracy was confirmed by postnatal exams, excluding those newborns that were not followed. See Table 5-1.
### Table 5-1

**Congenital Heart Disease Characteristics and Gestational Age**

<table>
<thead>
<tr>
<th>n=14</th>
<th>Frequency</th>
<th>Weeks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hypoplastic Left Heart</td>
<td>4</td>
<td>19-22</td>
</tr>
<tr>
<td>Hypoplastic Left Heart and Atrioventricular Septal Defect</td>
<td>1</td>
<td>21</td>
</tr>
<tr>
<td>Atrioventricular Septal Defect</td>
<td>3</td>
<td>18-22</td>
</tr>
<tr>
<td>Large Heart</td>
<td>1</td>
<td>21</td>
</tr>
<tr>
<td>Rhabdomyoma</td>
<td>1</td>
<td>26</td>
</tr>
<tr>
<td>Double Outlet Right Ventricle with pulmonary stenosis</td>
<td>1</td>
<td>24</td>
</tr>
<tr>
<td>Supraventricular Tachycardia</td>
<td>1</td>
<td>32</td>
</tr>
<tr>
<td>Double Outlet Right Ventricle, tetralogy spectrum</td>
<td>1</td>
<td>19</td>
</tr>
<tr>
<td>Tetralogy of Fallot</td>
<td>1</td>
<td>20-25</td>
</tr>
</tbody>
</table>

### Image Acquisition

In an effort to ensure a realistic evaluation of this approach, images were acquired using a variety of manufacturers’ sonographic imaging equipment and transducers including: Toshiba America Medical Systems Inc. (Tustin, CA), 4.0 and 5.0 MHz, curvi-linear transducer frequencies, Philips Medical Systems Inc. (Bothell, WA), 5-1 MHz, curvilinear transducer, General Electric Healthcare (Waukesha, WI), 4-8 MHz, curvilinear transducer and Siemens Medical Solutions USA, Inc. (Malvern, PA) 6-2 MHz curvilinear
transducer. Equipment settings were optimized to include a high frame rate, 30-100 Hz and harmonic imaging.

For both normal and abnormal cases three static images and two cine-loop sweeps were acquired. The static images included; the four chamber view, the left ventricular outflow tract view and the right ventricular outflow tract view. These images represented a conventional approach to image acquisition.

Using the same equipment settings as used in the conventional method and where possible the same acoustic window and fetal position two cine-loop sweeps were acquired. Each cine-loop sweep was acquired using a four second electronic capture stored to the local hard disk. The first cine-loop sweep is described as the situs-four chamber sweep. The technique used is described as follows; using a transverse abdominal section, the transducer was moved cephalad from the abdominal circumference into the four chamber view, without changing angles to the fetus, see Figure 5-1.
Figure 5-1

Cine-loop Acquisition

Orientation of cine-loop sweeps relative to the sagittal plane of the fetus. The first cineloop sweep begins at the abdominal circumference and continues cephalad into the four chamber view. The second sweep begins in the four chamber view and with a slight rotation towards the fetal left shoulder, angles cephalad through the outflow tracts.

Acquisition of the image should begin showing situs, capture at least two beats of situs in order to allow the interpreting physician to be able to appreciate the pulsatility of the aorta, then slowly slide the transducer cephalad without changing the angle. The acquisition should then end after documenting two cardiac cycles using the four chamber view. The second cine-loop sweep is described as the four chamber-outflows sweep. To acquire this cine sweep, the following technique was used: from the four chamber view, the transducer is rotated slightly toward the fetal right shoulder and angled cephalad; the LVOT is visible first with
cephalic angulation. The transducer is then angled more cephalad and to the left shoulder to visualize the right ventricular outflow.

**Image Review**

Both abnormal images and normal images were collated into an image data set representing 79 normal cases and 14 abnormal cases which totals to 93 distinct pregnancies. An online computer generated randomizer (random.org) was used to compile these image data sets in random order. There were seven image reviewers divided into three classes: expert, non-expert radiology residents and sonographer. There were two experts, a pediatric cardiologist, (E2) with more than ten years clinical experience and a pediatric cardiac sonographer with more than ten years’ experience, (E1), three non-experts, radiologists (NE1, NE2 and NE3), and two sonographers each with more than five years’ experience (S1, S2). Each of the image reviewers, blinded to one another’s results, worked through 93 sets of static images sequentially using the same randomized series. Upon completion of their review and interpretation of these they went on to review and interpret 93 sets of the abdomen to four chamber and four chamber to outflow cine-loop sweeps. Their image review was enabled through the use of a software program, Fetal Heart Sonographic Assessment Tool (FSAT), see Figure 5-2. This software allowed them to electronically record their assessments using an electronic check list that confirms demonstrations of five key points; 1) Situs, Position, Size; 2) Four chamber morphology; 3) Left ventricular continuity; 4) Right ventricular continuity and 5) the LVOT/RVOT relationship.
Figure 5-2

Fetal heart Sonographic Assessment Tool (FSAT),

The images displayed as statics or cine-loop sweeps in panel A. Decision making tool depicted in panel B, N represents a normal finding, A, an abnormal finding and NS means the structure or relationship was not seen.
A second electronic record was made to determine one of 3 outcomes: normal, abnormal or indeterminate. In order to set a comparable decision making process, each reviewer was advised that a normal decision would imply no further imaging or follow-up, an indeterminate selection would imply a follow-up ultrasound exam and an abnormal decision would be referred to the pediatric cardiology laboratory for further examination.

Statistical Analysis
The statistical significance of the detection rates provided by the image reviewers was determined using the McNemar chi-square test for a difference of proportions with significance level, \( p < .001 \). All other data was analyzed using a one-way analysis of variance (ANOVA). The analysis was performed using the Analyse-it Software, Ltd. (Leeds, UK).

Results
The expert reviewer (E1) detected 50% of the CHD using the static images and detected 93%, \( (13/14) \) of them using the cine-loop sweeps, see Table 5-2. The detection rate varied most within the cine-loop sweeps in both the expert and non-expert groups, where the detection rate varied by 29% and 28% respectively. The greatest improvement in detection between assessment methods was found in the non-expert group (NE3) with an improvement of 64%, the least improvement was found in the sonographer group (S2) with no difference observed. For all other reviewers the detection rate improved from 7%-64%.
The experts detected the most CHD with an average rate of 43% for the static images and 79% using the cine-loop sweeps, see Table 5-3 as an example. The non-expert group identified on average only 14% of CHD using static images and 52% using the cine-loop sweeps. Sonographers identified only 18% using the static images and nearly the same detection rate, 21% for the cine-loop sweeps.

### Table 5-2
Detection Rate by Reviewer, Experts (E), Non-Experts (NE), Sonographers (S), Number (%)

<table>
<thead>
<tr>
<th></th>
<th>(E1)*</th>
<th>(E2)</th>
<th>(NE1)</th>
<th>(NE2)</th>
<th>(NE3)*</th>
<th>(S1)</th>
<th>(S2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static</td>
<td>7 (50)</td>
<td>5 (36)</td>
<td>3 (21)</td>
<td>2 (14)</td>
<td>1 (7)</td>
<td>1 (7)</td>
<td>4 (29)</td>
</tr>
<tr>
<td>Sweep</td>
<td>13 (93)</td>
<td>9 (64)</td>
<td>6 (43)</td>
<td>6 (43)</td>
<td>10 (71)</td>
<td>2 (14)</td>
<td>4 (29)</td>
</tr>
</tbody>
</table>

*Statistically significant, p<.001

### Table 5-3
Average Detection Rate by Group, Experts (E), Non-Experts (NE), Sonographers (S), Number (%)

<table>
<thead>
<tr>
<th></th>
<th>(E) (2)</th>
<th>(NE) (3)</th>
<th>(S) (2)</th>
<th>All Reviewers (7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static</td>
<td>6 (43)</td>
<td>2 (14)</td>
<td>2.5 (18)</td>
<td>3.4 (24)</td>
</tr>
<tr>
<td>Sweeps</td>
<td>11 (79)</td>
<td>7.3 (52)</td>
<td>3 (21)</td>
<td>7.1 (51)</td>
</tr>
<tr>
<td>Change</td>
<td>+5 (36)</td>
<td>+5.3 (38)</td>
<td>+0.5 (3)</td>
<td>+3.8 (27)</td>
</tr>
</tbody>
</table>

The number of false positive cases identified overall by image reviewers was quite low with an average of 5.4% observed in the
static image review compared with 3.9% using the cine-loop sweeps.

**Discussion**

The analysis of the cine-loop sweeps resulted in an improved detection rate compared with the static images for expert and non-experts of 36% and 38% respectively. The nearly equivalent rate of improvement found in both groups suggests that the value of the cine-loop sweeps is equally applicable to the expert and non-expert interpreting physician. Within the non-expert group the variation in detection rate was 14% for the static image review and 28% for the cine-loop sweeps. This pattern of increased variation in detection rate for the cine-loop sweeps was also observed in the expert group. In this group the variation in detection rate for the static image review was 14% and 29% for the cine-loop sweeps. The increased variation between the reviewers may be explained by the fact that the cine-loop sweeps provided significantly more image information for analysis allowing individual interpretive skills to be demonstrated to a greater degree than the static images. The detection rate of non-expert reviewers using static images was only 14%. This result is in alignment with the reality that the static images of the four chamber and outflow tracts provide a very minimal amount of diagnostic information to the interpreting physician during the image review process. However, the expert reviewers were able to identify 43% of CHD using the same static images while maintaining a low rate of false positive identification. This difference suggests that the importance of training and
experience makes a significant impact on the detection rate of CHD. Surprisingly, the sonographers’ improvement in detection rate using the cine-loop sweeps compared with the static images was only 3% and this finding was not consistent with that of the expert and non-experts results. The sonographers detection rates overall were low, 21% using the cine-loop sweeps and 18% for the static images. Compared with the performance of the expert and non-experts, this low detection rate suggests that the interpretative expertise of the less experienced sonographers was not as refined compared with the physicians. This is not surprising since the role of a beginner sonographer is primarily image acquisition, initial review and limited interpretation skill, whereas; the interpreting physician’s role is primarily analysis and interpretation. These results indicate that it is essential that the interpreting physician have access to real-time sweeps of the heart if the goal is to detect CHD in routine obstetrical screening, although diagnostic findings would be improved by a full fetal exam which this research did not address. Furthermore, the cine-loop sweeps can be shared electronically via a secure network connection should the interpreting physician request expert consultation.

The average rate of false positive identification of CHD for all reviewers was 5.4% using the static images and 3.9% using cine-loop sweeps. This suggests that the reviewers understood the potential emotional impact and stress that a positive finding would have on the parents and families affected and they set the threshold for a positive finding relatively high. This might help
explain why the experts and non-expert detection rates did not exceed 80% even with the use of cine-loop sweeps.

All fourteen abnormal cases were identified using the cine-loop sweeps and two cases, a large heart and a hypoplastic left heart were identified by all seven reviewers. In contrast, two cases, atrioventricular septal defect and double outlet right ventricle with tetralogy spectrum were missed by all seven reviewers using the static images. An example is described below where the static images provided a false impression of normalcy compared with the cine-loop sweeps. In order to illustrate this, a frame was grabbed from the cine-loop sweep using a VLC media player 2.0.3 Twoflower© to demonstrate the pathology. In Figure 5-3, a normal looking four chamber view is contrasted with a more abnormal looking view extracted from the cine-loop sweep. This was confirmed as a Tetralogy of Fallot. Only one of the seven reviewers identified this pathology on the static images. These findings further underscore the need for an assessment in real-time.
Figure 5-3

The ventricular septal defect associated with this example of Tetralogy of Fallot is best demonstrated in image A, a frame selected from the cine-loop sweep as compared with image B a static image acquired as a single image using the conventional technique.
While the results of this study uniformly point towards the increased value of the cine-loop sweeps as compared with the static images, due to the relatively small sample of 14 cardiac defects, statistical significance was achieved in the results in only two of the seven reviewers. Not included in our study however, was the three vessel view which has been found to be a very effective method of assessing the ventricular outflow tracts (Yoo, Lee, Kim, Ryu, Choi, & Cho, 1997). In a pilot study it was found that the majority of screening centres in our region were acquiring the four chamber and outflows as three static images, and the acquisition of the three vessel view increased the acquisition time significantly compared with the two sweeps described above (Scott et al., 2008). Our approach is intended to incorporate cine-loop sweeps into a routine, second trimester sonogram with a minimally added acquisition time and sonographer training. It was for these reasons we chose not to include the three-vessel view. The abnormal cases were acquired in a prospective fashion based on availability to the researchers and therefore they do not represent a comprehensive sample of CHD. Hypoplastic left heart cases are over represented along with atrial ventricular septal defects in this sample.

**Conclusion**
The use of cine-loop sweeps is a practical and standardized approach to the assessment of the fetal heart during routine obstetrical sonograms. This technique poses several advantages compared with review of static images, it has been shown to increase the rate of detection of CHD while minimizing the false
positive identification. The acquisition process is a relatively simple procedure and does not require additional resources other than the capacity to store cine-loops within the clinical facility.

The results of this study support the use of standardized procedures, both for acquisition of images as well as their review and interpretation.

By including real-time cine-loop sweeps through the fetal heart in a standardized format, the interpreting physician gains access to additional critically important evidence not obtained by three basic images to guide their decision making. This study demonstrates a possible improvement in prenatal detection of congenital heart disease when standardized cine loops and checklists are included in the prenatal cardiac screening review by expert and non-expert clinicians. Despite the small sample size, statistically significant improvement in congenital heart defect detection was demonstrated with two out of seven reviewers. On the basis of these findings, further study with a larger sample size and a more complex research design may support inclusion of cine-loop sweeps as well as increased two-dimensional views in routine prenatal screening programmes.
Chapter 6 Increasing Recognition of Fetal Heart Anatomy using Online Tutorials and Mastery Learning compared with Classroom Instructional Methods

Introduction
The majority of deaths from congenital defects in childhood can be attributed to congenital heart disease (CHD) (Gilboa et al., 2010). The most common cause of birth defects, CHD is most frequently reported with an incidence of 0.8% of all live births (Dolk, Loane, & Garne, 2011). The prenatal diagnosis of congenital heart disease can improve clinical outcomes of those affected after birth (Brown et al., 2006; Cass, 2011; Fuchs et al., 2007). Prenatal diagnosis of congenital heart disease is critically important to ensure: optimal management of the pregnancy, optimal delivery of the baby and provision of support for parental decision making. In addition, those at high risk for CHD may be relieved of additional anxiety and fears due to the possibility of CHD by confirmation of normality (Allan & Huggon, 2004).

The role of the sonographer in prenatal diagnosis of congenital heart disease is to assess the fetal heart in real-time including the four chambers and the outflow tracts (American Institute of Ultrasound in Medicine, 2013; Eik-Nes, 2006). Typically the obstetric sonographer will document normal or abnormal findings as a preliminary report with corresponding static images. The interpreting physician will review the preliminary report and associated images confirming the determination of a normal, abnormal or indeterminate finding.
The formal training for diagnostic medical sonographers in the detection of congenital heart defects is provided in didactic form usually within an obstetrics and gynecology sonography course. The clinical practicum is most often provided through clinical facilities linked to the college program. Imaging and assessing the fetal heart is a challenging task for sonography students. Unlike abdominal, pelvic or other sonography exams, students usually do not have an opportunity to practice obstetrical sonography in their college imaging laboratories. It is also difficult for education programs to acquire a robust library of sample cases representative of the diversity of congenital heart disease. Assessing the fetal heart and acquiring images is a complex task demanding an integrated understanding of the cardiac embryology of the fetal heart and morphologic changes with pathology. Image recognition skills for identifying rapidly moving structures such as the outflow tracts on the order of 2-6 mm in diameter are intimidating to an imaging learner (Allan, 2004).

Addressing complex learning objectives that demand significant skill development by the learner is a challenge for the traditional classroom setting. Skill development demands significant formative assessment and structured feedback which can be difficult to provide to a group in a classroom environment. For teachers at all levels of education, it remains a challenge to provide customized instruction and high quality feedback to individuals in large classes.

In a seminal article in 1984, Benjamin Bloom articulated a number of methods to address the two sigma problem. Bloom found that
using both mastery learning and tutorial based instruction compared with conventional classroom instruction, students in the tutorial and mastery learning groups on average increased their achievement levels by two sigma (standard deviations) (Bloom, 1984). In other words, the average student in the tutorial and mastery group outperformed 98% of the students in the classroom group (Bloom, 1984). Mastery based instruction proposes that learning should provide formative evaluation with guided or corrective feedback such that students achieve mastery of all of the learning objectives (Gagné & Bloom, 1988). Tutorial based instruction assumes that students are working regularly with a good tutor, in a face to face mode. Two forms of instruction have emerged to address the opportunity for learning using the theory of the two sigma problem (Corbett, 2001). These forms include a method of automated feedback based on student performance during practice exercises and mastery learning, where students work at their own pace to achieve mastery of learning (Corbett, 2001; Svinicki, 1999).

In the realm of digitally enhanced education that exists in many postsecondary institutions today, there exists a significant opportunity to provide students with opportunities to leverage the educational theories and applications established by Bloom. Some very popular solutions have emerged from outside the traditional postsecondary sector. Khan Academy is a very popular electronic platform for learning mathematics that uses tutorial-based instruction and mastery learning principles (Khan, 2012). Students are able to traverse the entire spectrum of mathematics necessary
to achieve successful preparation for entry into postsecondary institutions. Besides the pedagogical advantages associated with the two sigma problem, the use of electronic learning tutorials and practice exercises provide numerous advantages compared with traditional classroom learning. These advantages include:

- Ensure a consistent and high quality learning opportunity
- Self-paced progress through the learning objectives
- Opportunity to repeat tutorials without reliance on a human tutor
- Ability to access experts on niche topics
- Expand the learning opportunity to a global audience in any language
- Provide tutorial and learning tool designers valuable quantitative feedback regarding the learning experience
- Feedback can be used to improve future iterations of the tutorials and tools

The objective of the research was to determine if online tutorials and practice exercises using a standardized assessment of the fetal heart in real-time is a more effective approach to be used by students when learning how to identify normal fetal heart structures and congenital heart disease. The hypothesis was that "Training students to use a standardized assessment technique using tutorials and practice exercises online compared with traditional classroom instruction will increase the student’s ability to identify normal fetal heart structures and congenital heart disease."
**Materials and Methods**

This study was approved by the Charles Sturt University Ethics in Human Research Committee, the McMaster University Research Ethics Board (MREB) and the Mohawk College Research Ethics Board.

The participants in this study were drawn from the Medical Radiation Science, Obstetrical and Gynecologic Ultrasonography 3 course. Sonography students were in the third year of study within a collaborative four year, Mohawk-McMaster Medical Radiation Sciences program. All students in the class chose to participate in this study. The total number of all participants was 33. From the initial 33 participants, 27 students completed all of the learning activities and the final quiz, 15 students from the experimental group and 12 students from the control group.

Three learning objectives for the experimental and control groups are defined as follows:

1. Increase ability to identify normal fetal cardiac structures
2. Increase ability to identify abnormal fetal cardiac structures
3. Increase ability to identify abnormal cases

Students were randomly divided into two groups. There were 17 students assigned to the classroom learning group (control) and 16 were assigned the online learning, (experimental) group. Students assigned to the control group were not permitted access to the online tutorials and practice exercises. Students assigned to the
experimental group were not permitted to attend the four teacher led classes and single online tutorial with the course instructor. The online exam was administered within two weeks of the onset of the experiment.

Students enrolled in the control group participated in four classroom lecture periods of 50 minutes each and one online tutorial. The lectures reviewed the anatomy of the fetal heart, the fetal blood flow and the sonographic views used to image the heart. They also included real time loops with tips and suggestions on how to identify a normal heart. Lectures included review of some of the more common congenital heart abnormalities using real time loops. The tutorial was delivered online with labeled anatomy images with focused questions pertaining to the diagrams. The time for instruction was approximately 240 minutes and an allowance for independent study time of approximately 90 minutes for a total of 330 minutes of time committed to learning.

The experimental group was provided with the “Find it First” tool consisting of 13 brief online tutorials in the use of a five step method of the fetal heart assessment prepared by the study investigator, amounting to approximately 75 minutes of instruction in total. Students completed practice exercises online as formative assessment with electronic feedback that required an additional 150 minutes of learning time. The total time committed to learning for the experimental group was approximately 225 minutes.
The students were also provided practice cases for each step of the technique and these exercises included immediate electronic feedback. Students were required to demonstrate mastery of each step before continuing to the next step of assessment. A screen shot depicting the user interface for the practice exercises provided by module two is provided in Figure 6-1. Students worked through five online modules representing five steps of analysis considering the anatomic features and relationships as follows;

1. Cardiac situs, position and size
2. Chamber morphology and function
3. Left Ventricular Outflow Tract (LVOT) continuity with the left ventricle
4. Right Ventricular Outflow Tract (RVOT) continuity with the right ventricle
5. Normal cross-over of outflow tracts at their origins
During formative assessment the feedback is provided immediately. All cases that are incorrect must be repeated after the first practice series is completed before continuing to the next learning module.

Each of these features and relationships could be defined as normal, abnormal or not seen. Each module consisted of a brief tutorial to provide examples and instruction on how to assess the
relevant anatomic feature. Following the review of each tutorial the students were required to complete 17 sample cases as depicted in Figure 6-1. At the end of every series, all of the missed cases were compiled and the learner re-assessed the missed cases until all 17 cases were accurately reviewed. The student could advance to the next module only after successfully demonstrating the ability to analyze the anatomic features covered by the module. As students advanced through the modules, additional steps were added to the analysis until the student reached the fifth module where all five steps and corresponding features were examined representing a review and analysis of a total of 85 cases.

In order to assess the performance of the students in both groups, an online quiz was developed. Each student was provided with a unique and secure user identification and password. Students’ ability to identify normal and abnormal structures was measured by their review of 25 cases of fetal cardiac anatomy. A randomized sequence of 10 abnormal and 15 normal cases were presented. Each case consisted of two cine-loop sweeps through the fetal heart, the abdomen to four chamber sweep began in the transverse abdominal plane at the level of the stomach and ended at the four-chamber view. The four-chamber to outflows sweep began in the four chamber view and swept through the ventricular outflow tracts. Students in both groups completed the online examination within two weeks of completing the classroom or online instruction. As described in Figure 6-2, students were required to identify 5
anatomic features for each case and determine whether that case is either, normal, abnormal or indeterminate.

**Figure 6-2**
The final quiz includes the assessment of all five indicators and the final decision.

A completely accurate assessment was one that scored each feature accurately and correctly identified the case as normal, abnormal or indeterminate. The decision framework was standardized for the students using a protocol that defined the following outcomes: a normal result implies no further assessment, an abnormal determination will result in a referral to a pediatric cardiologist, and an indeterminate finding will result in a follow-up
reassessment in the obstetric screening center. This evaluation required approximately one hour for the students to complete.

Data Analysis

The Chi Square test was performed to evaluate the statistical significance of the image analysis results. The null hypothesis for this test was defined by the following statement, “After using the computerized learning system (experimental group) or gaining instruction in a traditional face to face classroom environment (control group), there will be no statistical difference in students’ ability to identify normal and abnormal fetal heart structures.” Differences on the multiple choice evaluations and the confidence levels were compared using the Student t-test for statistical significance.

Results

The students were evaluated on their ability to correctly assign one of three conditions, normal, abnormal or not seen to five unique anatomic criteria and relationships and correctly define the case as normal abnormal or indeterminate. For each case to be scored as completely correct, all five anatomic criteria and the assignment of normal, abnormal or indeterminate must be correct. This required a total of six correct decisions for each case, by the student. The students in the control group on average assessed correctly all five anatomic features and determined the normal or abnormal status of only 4.7/25, +/- 4.4 (standard deviation) compared with the experimental group mean score, 9.9/25, +/- 2.7 (standard deviation), P<.01. Students in the control group identified 19% of
the cases correctly compared with 39% for the experimental group. In terms of mean performance difference between the two groups there was a one sigma effect. This means that the average score in the experimental group was greater than 84% of the students in the control group. Furthermore, as seen in Table 6-1, the experimental group outperformed the control group in every category of assessment.

**Table 6-1**

Five points of assessment of the fetal heart and the percentage of complete exams correctly identified as normal, abnormal or not seen. Students in the experimental group (Series 1) used the online tool compared with students in the control group (Series 2) who participated in classroom learning.
Table 6-2
Detection rate by group according to the individual cases of congenital heart disease.

<table>
<thead>
<tr>
<th>Case</th>
<th>CHD, n=10</th>
<th>Experimental Group, n=15</th>
<th>Control Group, n=12</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Detected (%)</td>
<td>Detected (%)</td>
<td>(%)</td>
<td></td>
</tr>
<tr>
<td>1  Large Heart</td>
<td>13 (93)</td>
<td>7 (58)</td>
<td>(35)</td>
<td></td>
</tr>
<tr>
<td>2  Truncus Arteriosus</td>
<td>12 (80)</td>
<td>9 (75)</td>
<td>(5)</td>
<td></td>
</tr>
<tr>
<td>3  Hypoplastic Left Heart</td>
<td>12 (80)</td>
<td>6 (50)</td>
<td>(30)</td>
<td></td>
</tr>
<tr>
<td>4  D-TGA</td>
<td>11 (73)</td>
<td>7 (58)</td>
<td>(15)</td>
<td></td>
</tr>
<tr>
<td>5  Single Ventricle</td>
<td>10 (67)</td>
<td>6 (50)</td>
<td>(17)</td>
<td></td>
</tr>
<tr>
<td>6  AVSD</td>
<td>7 (47)</td>
<td>5 (42)</td>
<td>(5)</td>
<td></td>
</tr>
<tr>
<td>7  Tetralogy of Fallot</td>
<td>7 (47)</td>
<td>2 (17)</td>
<td>(30)</td>
<td></td>
</tr>
<tr>
<td>8  Hypoplastic Left Heart</td>
<td>7 (47)</td>
<td>7 (58)</td>
<td>(-11)</td>
<td></td>
</tr>
<tr>
<td>9  Tetralogy of Fallot</td>
<td>3 (20)</td>
<td>4 (33)</td>
<td>(-13)</td>
<td></td>
</tr>
<tr>
<td>10 Ebsteins Anomaly</td>
<td>1 (7)</td>
<td>4 (33)</td>
<td>(-26)</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>83 (55)</td>
<td>57 (48)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The abnormal cases as depicted in Table 6-2, represent a typical range of serious congenital heart disease. One or more abnormal anatomical features were evident in the cine-loops provided to the students for review. As defined in Table 6-2, the experimental group outperformed the control group in 7/10 abnormal cases, p<.01. Specifically in five abnormal cases, D-TGA, Single Ventricles, Large Heart, HLHS and Truncus Arteriosus, a greater than 2/3 majority of experimental students identified these cases whereas the control group only identified 1 case, Truncus Arteriosus by a 2/3 majority of students, p<.01. The experimental group performed particularly
poorly in detecting Ebsteins anomaly, 7% detection compared with 33% for the control group.

Discussion
The strategy adopted by most sonography programs for teaching students to identify the presence of pathology during abdominal or pelvic examinations is typically based on providing students with clinical practice and exposure to normal sonographic appearances of anatomic structures. In teaching students to identify the presence of pathology, sonography programs progress from a focus of normal findings towards a framework for pathology such that students can focus their attention on links between the patient's history and the probable associated pathology. Part of the challenge for detecting congenital heart disease in-utero is the fact that most often it is found unexpectedly in the low-risk population (Sharland, 2004). This makes it more difficult to detect because one cannot usually rely on clues from the patient history to focus the examination. Furthermore, as a screening examination, the inherent bias is an expectation of normalcy. Standardizing imaging procedures and assessment protocols represent an important consideration in this regard and one that was adopted for this learning tool.

In addition to the two sigma pedagogy, the online learning tutorials and practice exercises focused nearly exclusively on exposing students in the experimental group to as many normal and abnormal cases as possible in a step-wise learning methodology. The focus for the learner was on practicing the decision making for
each step in each module until mastery of the concept was achieved. In the classroom learning group, a broader focus was taken and students were given more contextual information related to the normal and abnormal heart. There was less emphasis on skill development with feedback in the classroom setting.

Bloom’s two sigma theory was not replicated in this study; however, a one sigma improvement was found and this represents a two-fold increase in the percentage of cases accurately classified by students in the experimental group, 39% which was compared with 19% in the control group. Further, the experimental group did not benefit from any face to face learning opportunities. This might also explain why a two sigma effect was not achieved. The ability to correctly classify, anatomic features and relationships was consistently demonstrated across all five categories. This suggests that students acquired improved image interpretation skills in the experimental group as compared to the control group.

Seven out of ten of the congenital heart defects were identified with greater frequency by the experimental group compared with the control group. In addition, the experimental group was much more consistent as a group in identifying five out of ten defects with a greater than 2/3 majority of the group compared with the control group which only achieved a 2/3 majority correct identification for one abnormal case. These results suggest that the use of mastery based instruction in the form of practice exercises that are framed in a step-wise protocol might lead to a more consistent development of image interpretation skills. The particularly poor performance of
the experimental group with respect to the Ebstein’s Anomaly may be due to the fact that it was not included as an example during the online tutorials and it represents the singular isolated abnormality of an apical displacement of the tricuspid valve. The online tutorials emphasized more frequently encountered structural abnormalities including the presence of ventricular septal defects, discontinuity of the outflow tracts, disparity in chamber size, heart size and angulation. Future versions of this learning tool will correct this oversight.

This study had significant limitations. The number of participants was relatively small and representative of a single cohort of sonography students. Five of the 17 students in the control group did not complete the study while only one of the students in the experimental group did not complete the study. The students in the experimental group may have persisted through the final evaluation and completed the study in greater number due to their familiarity with the “Find it First” learning tool. Some of the students from the classroom (control) group may have found the final evaluation provided on the “Find it First” tool to be unfamiliar and this may have been enough to deter them from completing the study. Another limitation may be that the online learning tutorials and practice exercises were first generation and improvements in image quality and consistency, and technical terms can be better achieved in future generations of this application. Furthermore the performance of the students in the control (classroom) group is
dependent on a single instructor which could bias the outcome of the students’ learning in either a positive or negative direction.

**Conclusion**
In this study, it was shown that, students’ abilities to correctly classify normal and abnormal fetal cardiac anatomy can be improved using principles of mastery learning and tutorial-based instruction in an online format. Further, the opportunity to exploit the benefits of online learning may provide students with greater access to high quality learning opportunities. Students may benefit from a self-paced approach to learning with the opportunity to review tutorial sessions as much as desired.

Assessment of the fetal heart for congenital heart disease is a challenging task and one that demands significant educational expertise in the domains of cardiovascular and obstetrical practice areas. For topics that demand complex analysis and clinical expertise at the intersection of clinical skills such as fetal cardiac assessment, an online tutorial-based approach may prove to be very effective means of addressing this teaching and learning challenge.

This study demonstrated that students using the online tutorial and practice exercises had improved performance by one standard deviation compared with students using traditional classroom based learning methods. Further, examination of this approach including quantitative analysis of the user experience may identify opportunities to refine and improve learning approaches specific to assessments of the fetal heart. Future studies may demonstrate
benefits to other stakeholders including practicing clinical
sonographers and interpreting physicians. It may prove worthwhile
for other educational applications to be developed using this
methodology, particularly those areas of clinical ultrasound that are
not fully addressed through traditional curriculum.
Chapter 7 State of the Art and Future Opportunities

**Summary of Research Studies**
Increasing the detection of CHD during routine obstetrical sonograms remains a challenge for sonographers and interpreting physicians. The impact of early detection is significant, creating the opportunity for counseling, enhanced management and treatment of the pregnancy, potential identification of additional pathologies and possible decreased morbidity (Allan & Huggon, 2004; Bonnet et al., 1999; Sklansky et al., 2002).

The interpreting physician’s reliance on limited static images of the fetal heart during the routine obstetric sonogram has not been a successful approach for identifying most CHD to date (Oggè et al., 2006; Stumpflen, Stumpflen & Wimmer, 1996). This PhD research describes a new approach to address the limitations associated with reliance on only static images to identify CHD. A pilot study was completed to compare three techniques: 1) conventional technique capturing only three static images of the fetal heart; 2) two grey-scale sweeps through the fetal heart and; 3) two grey scale with colour Doppler sweeps. The greyscale sweeps were found to provide enhanced information to more effectively assess the fetal heart compared with static images only. A complete cardiac assessment was achieved in 71% of studies using grey scale sweeps technique compared with 39% of static image acquisitions. The colour Doppler technique provided additional blood flow information of the atrial-ventricular valves in 86% of subjects. However, the use of colour Doppler was found to
negatively impact the visualization of other normal fetal heart structures, and add significant examination time to the sonogram.

The grey scale sweeps imaging technique coupled with a five step assessment method has been shown to be a practical and standardized approach to the assessment of the fetal heart during routine obstetrical sonograms. This technique poses several advantages compared with the review of limited static images only. It has been shown to increase the rate of detection of CHD while minimizing the false positive identification of CHD. Furthermore the acquisition and assessment process is a relatively simple procedure and does not require additional resources, other than the capacity to store cine-loops within the clinical facility.

By providing cine-loop sweeps instead of static images only, the physician gains access to critically important evidence to guide their decision-making. For cases that are not easily classified as normal or abnormal, cine-loop sweeps can be shared with expert consultants in order to provide greater clarity and certainty in the decision-making process. Standardizing the assessment process ensures that a consistent and thorough examination of the fetal heart is conducted.

Enabling sonographers and interpreting physicians with the opportunity to learn and practice the five step standardized assessment depends on the availability of suitable learning resources. An online learning tool, the “Find it First” web based application was developed to ensure that sonographers,
interpreting physicians working in the field, and students would have access to tutorials, practice exercises and quizzes to enhance image recognition skills. The “Find it First” learning tool, was deployed to evaluate the impact of online tutorials with practice exercises and automated feedback using mastery-based instruction compared with traditional classroom instruction in a quasi-experimental study. It was shown that students’ ability to correctly classify normal and abnormal fetal cardiac anatomy can be improved using principles of mastery learning and tutorial-based instruction. The tool is widely accessible as a web-based application and exploits the strengths of online learning providing students with unlimited, self-paced learning opportunities.

**Feedback loops**

Both the sonographer and the interpreting physician have roles and responsibilities related to the identification of abnormalities during routine obstetrical screening. The sonographer is typically responsible for completing an extensive survey of both maternal and fetal anatomy. The objective of this survey is to document normal features and identify abnormal findings. The role of the interpreting physician is to review the sonographer’s findings most often in the form of an electronic check list or hand written notes along with static images. This creates a feedback loop between the sonographer and interpreting physician which works well for most of the obstetric examination. Due to the motion of the fetal heart and its complexity, the review of static images only compromises the quality of this feedback loop. Where there is discordance between
the sonographer and interpreting physician, the physician may rescan the patient or request a follow-up examination. The real-time standardized assessment proposed in this thesis has the potential to improve the detection rate of congenital heart disease and increase productivity by reducing the discordance between the sonographer and the interpreting physician.

Standardized protocols for acquisition and assessment of real-time cine-loop sweeps provide stronger feedback loops between the sonographer and the interpreting physician. In a sense, the interpreting physician will now have access to the same quality of information as the sonographer. The cine-loop sweeps become a common reference point that can elicit a higher quality feedback loop between the sonographer and the interpreting physician.

Another critically important feedback loop can be created for the learning process. Using the “Find it First” web application, learners including sonographers and interpreting physicians receive immediate feedback on their classification of fetal cardiac anatomy and the determination of the case as normal, abnormal or indeterminate. This ensures that the learner is able to identify their mistakes and knowledge gaps as they work through the practice exercises and re-visit tutorials and practice exercises. The ability to review their work and identify gaps in their knowledge online provides learners with a self-paced learning opportunity. Using standardized tools provides the learners with the practice and feedback needed to improve their image recognition skills until they achieve mastery.
A model for Improving Screening Techniques

In summary, the likelihood of increasing the detection rate of CHD during routine obstetrical sonograms depends on the commitment by the screening center staff to standardize a high quality imaging process. Optimal screening for the presence of congenital heart disease demands a commitment to five key facets of the process:

1. Image optimization
2. Acquisition standards
3. Image review
4. Interpretation protocol
5. Regular image recognition skills development with structured, consistent feedback.

Assessment of the fetal heart for congenital heart disease is a challenging task and one that demands significant educational expertise in the domains of cardiovascular and obstetrical practice areas. Fetal cardiac assessment demands complex analysis and clinical expertise. Clinical skills development utilizing an online tutorial-based approach may prove to be a very effective means of addressing this teaching and learning challenge.

Future studies may demonstrate benefits to other imaging examinations, particularly those areas of practice that are not fully addressed through traditional curriculum. Examples where online tutorial-based instruction might be developed include other areas of
sonography including, but not limited to, musculoskeletal imaging, and volume imaging.

Given that screening for the presence of specific congenital anomalies or disease is conducted on other body parts and systems such as breast and vascular structures, other screening programs may benefit from adopting the model described above. In other screening programs such as carotid or abdominal aortic artery screening, standard imaging protocols are used and, in some cases, governed by accreditation processes. At present the availability of image recognition and skills-oriented learning tools online is very limited. A gap exists for opportunities to receive self-paced, mastery-oriented imaging learning opportunities. In the future, many such applications will be developed to enable access to high quality learning opportunities.
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(Candidate authored papers)


Appendix A

Project Protocols and Design Considerations

Project #1, pilot study, project proposal summary, protocol and sample size estimate

Improving the Detection Rate of Congenital Heart Defects Using a Real-Time Cardiac Assessment Technique in Routine Obstetrical Screening

ABSTRACT

My PhD thesis is entitled, “Improving the Detection Rate of Congenital Heart Defects Using a Real-Time Cardiac Assessment Technique in Routine Obstetrical Screening”. I have planned two projects that will allow me to successfully complete this program of study. I have funding for this work from the SDMS Educational Foundation, Graduate Research Award and the Bracco Ultrasound Research Award for the first of these projects. The first is described as phase one and the second one is described as phase two. The phase one project is entitled, “Comparison of static, real-time and real-time, colour Doppler imaging techniques applied to the assessment of the fetal heart in routine screening”. This project will identify the optimal imaging protocol for the routine assessment of the fetal heart during obstetrical screening taking into account the limitations of time and technology imposed on the sonographer during routine second trimester screening. The phase two project will be much larger in scope and it is entitled, “Comparison of the basic extended fetal cardiac screening technique with a real-time technique for the detection of congenital heart defects”. The goal of this study will be to demonstrate an improved detection rate of congenital heart defects using the technique identified in phase one.
SYNOPSIS OF LITERATURE

The use of ultrasound imaging for routine fetal screening in the second trimester has been adopted by the Canadian health care system and a number of European countries as a standard of care (Johnson 2005). According to a survey of 2758 referrals to the fetal cardiology unit at Guy’s Hospital, London, UK, the low risk population for congenital heart defects is the source of 80% of congenital heart defects (Sharland 2004). This underscores the importance of routine screening for detection of congenital heart defects. Routine screening provides a more accurate measure of gestational age, earlier detection of multiple pregnancies and may detect congenital malformations. The Eurofetus study identified marked differences in sensitivity for detection of different malformations, abnormalities of the urinary system and nervous system were most easily detected with a sensitivity of 88.5% and 88.3% respectively (Johnson 2005). In this study cardiac abnormalities were not well detected, sensitivity for major cardiac defects was 38.8% and minor defects 20.8% (Johnson 2005). In Canada, the examination is performed in real-time and documented as a series of still images archived electronically or on film. The interpretation of the cardiac images is performed by a radiologist or obstetrician using the still images. Present detection rates for congenital heart defects (CHD) vary widely depending on a number of factors, operator skills, maternal obesity, fetal position, inadequate image optimization, visualization, of the four chamber view only. The American College of Radiology (ACR) and the International Society of Ultrasound in Obstetrics & Gynecology (ISUOG) have published new guidelines for routine second trimester screening that require the four chamber view and where possible views of the left ventricular outflow tract (LVOT) and right ventricular outflow tracts (RVOT) to address this limitation (ISUOG 2006, ACR 2003).
The objective of my research is to attempt to minimize operator dependence by providing the sonologist with real-time loops of fetal cardiac structures. My research assumes the ultrasound systems that are used are capable of Colour Doppler processing and are configured to store or transmit real-time loops to a network. The real-time loops will add considerable diagnostic value to the screening process since there will be two interpretations performed on every exam, the preliminary review by the sonographer and the summary review by the sonologist. In addition using the real-time loops will allow the sonologist the opportunity to review the images repeatedly in real-time and evaluate structure at different points during the cardiac cycle. The ability to assess structure during the diastolic phase has been found by Chaoui (2003) to be helpful in detecting atrioventricular septal defects. Further, it is well established that observation of moving structures provides a more sensitive means of detecting small differences in form (Ivry & Cohen, 1992). A cine loop of a sweep through the cardiac outflow tracts will allow the sonologist to better appreciate the relationship between the LVOT and RVOT which is crucial for ruling out conotruncal abnormalities. Hosono et al, (2002) found the use of tissue harmonic imaging to be advantageous in imaging fetal cardiac tumours due to improvements in image contrast. Using THI will improve the quality of the images and may influence the detection rate of cardiac structures as well. The advantages of using three basic Doppler planes have been well documented by Chaou, (2003). Adding these Doppler images aids in the identification of conotruncal abnormalities, valvular insufficiency and may reveal more subtle lesions such as ventricular septal defects (Chaoui, 2003).

PHASE ONE RESEARCH QUESTION/OBJECTIVES

Comparison of static, real-time and real-time, colour Doppler imaging techniques applied to the assessment of the fetal heart in routine screening
Research Aims

- Demonstrate the ability to acquire the experimental protocols, B and C in less than five minutes
- Demonstrate an increase in the image quality of the atria, ventricles and outflow tracts using THI and spatial compounding in subjects with a BMI >30 compared with conventional imaging
- Demonstrate an increased rate of detection of cardiac structures using real-time and real-time colour Doppler loops compared with static images
- Establish the presence of antegrade flow between the atria and ventricles
- Evaluate the ventricular septum for shunts
- Determine patency of the AV valves and semilunar valves

Methodology and Sample Size

There will be three protocols tested, acquisition of three static cardiac images, the four chamber view and longitudinal images of the LVOT and RVOT. This experimental protocol will be known as protocol A. An experimental known as protocol B will use THI and spatial compounding while acquiring two real-time loops, one of the four chamber view and a second that sweeps through the outflow tracts. A second experimental protocol C, will acquire three colour Doppler loops using the four chamber, five chamber and three vessel view.

The study sample size has been chosen to be 28 which is sufficiently large to allow identification of the normal cardiac structures and their relationships in a minimum of 19 subjects using the conventional technique and 9 cases using the experimental technique which gives a difference of 10 between two independent proportions with a power of 80% and $\alpha = .05$ (UCLA Department of Statistics, 2004).
Image Acquisition Guidelines

Patient name entry

No MRN or patient name to be entered. Only enter the study number in the MRN field

Example:
Surname: Fetal
First name: Study
MRN: Study 100

Real-time and Static images

- Images are acquired using a field of view that represents the fetal thorax as 75% of the field of view. The entire thorax must be visible in the field of view in all cases.
- Image presets are consistent from case to case. Use harmonics and maintain a frame rate of 30 frames/s minimum. Most fetal echo presets should provide this.

Real-time images:
- Configure the loops as 4 seconds in length
- Save as DICOM files to the hard disk

Images to acquire

- 3 still images:
  a. 4 chamber
  b. LVOT (long axis)
  c. RVOT (long axis)

- 2 loops (4 seconds) each
  a. Sweep from AC → 4 Chamber
  Sweep from 4 chamber → outflows
Reference


Chaoui, R 2003, ‘The four chamber view: four reasons why it seems to fail in screening for cardiac abnormalities and suggestions to improve detection rate’, Ultrasound Obstet Gynecol, vol. 22, pp.3-10


ISUOG Education Committee, ‘Cardiac screening of the fetus: guidelines for performing the ‘basic’ and ‘extended basic’ cardiac scan’, Ultrasound Obstet Gynecol, vol. 27, pp. 107-113


1.0 INTRODUCTION

The use of ultrasound imaging for routine fetal screening in the second trimester has been adopted by the Canadian health care system and a number of European countries as a standard of care. According to a survey of 2758 referrals to the fetal cardiology unit at Guy’s Hospital, London, UK, the low risk population for congenital heart defects is the source of 80% of congenital heart defects. This fact underscores the importance of routine screening for detection of congenital heart defects. Routine screening provides a more accurate measure of gestational age, earlier detection of multiple pregnancies and may detect congenital malformations. The Eurofetus study identified marked differences in sensitivity for detection of different malformations. Abnormalities of the urinary system and nervous system were most easily detected with a sensitivity of 88.5% and 88.3% respectively. In this study cardiac abnormalities were not well detected, sensitivity for major cardiac defects was 38.8% and minor defects 20.8%.

1.1 LIMITATIONS OF SCREENING

In Canada, an obstetric screening examination is performed in real-time and documented as a series of still images archived electronically or on film. The interpretation of the cardiac images is performed by a radiologist or obstetrician using the still images. Present detection rates for congenital heart defects (CHD) vary widely depending on a number of factors, operator skills, maternal obesity, fetal position, inadequate image optimization, and visualization of the four chamber view only. The American College of Radiology (ACR) and the International Society of Ultrasound in Obstetrics & Gynecology (ISUOG) have published guidelines for routine second trimester screening that require the four chamber view and where possible, views of the left ventricular outflow tract.
(LVOT) and right ventricular outflow tract (RVOT) to address this limitation.⁴,⁵

Acquisition of static images of the fetal heart provides a very limited quantity of diagnostic information, as the identification of normal cardiac structures cannot be completely demonstrated as a series of a few static slice images. The interpretation of key structural relationships can only be completed during a real-time interrogation. In practice the detection of the critical normal structures is accomplished solely by the sonographer. This approach limits the interpreter’s ability to confirm the findings of the sonographer.

1.2 A REAL-TIME APPROACH

Acquiring real-time loops will add considerable diagnostic value to the screening process since there will be two interpretations performed on every exam, the preliminary review by the sonographer and the summary review by the sonologist. In addition using the real-time loops will provide the sonologist the opportunity to review the images repeatedly in real-time and evaluate structures at different points during the cardiac cycle. The ability to assess structures during the diastolic phase has been found by Chaoui (2003) to be helpful in detecting atrioventricular septal defects.⁶ Further, it is well established that observation of moving structures provides a more sensitive means of detecting small differences in form.⁷ A cine loop of a sweep through the cardiac outflow tracts will allow the sonologist to better appreciate the relationship between the LVOT and RVOT which is crucial for ruling out conotruncal abnormalities.
1.3 PILOT STUDY

A PhD student identified for this project, Mr. Ted Scott, recently completed a pilot study (in press) that used a digital imaging network to store cine-loops of the fetal heart. Acquisition of real-time loops assumes the ultrasound systems that are used are capable of storing and transmitting real-time loops to a network. A survey of 21 local screening centers found that 95% of centers were acquiring and storing images electronically using a Picture Archiving Communications System (PACS). The majority of centers acquired three static images of the foetal heart, the four chamber view, the LVOT and RVOT view. For the purpose of this study this combination of static images represents the conventional technique, protocol A.

The purpose of this study was to determine if acquiring real-time sweeps of the foetal heart would be a more effective method of identifying normal cardiac structures compared with using static images during routine 2nd trimester obstetric sonograms. Subjects were scanned using three different techniques. The static image acquisition, protocol A, included three images of the foetal heart. Protocol B used two grey scale sweeps through the foetal heart. Protocol C acquired three colour loops of the foetal heart. The sweeps demonstrated a complete normal cardiac assessment in 71% of studies compared with the static image and colour Doppler techniques that completed a normal cardiac assessment in only 39% of studies respectively. The real-time technique detected four chambers, LVOT, RVOT, the LVOT/RVOT cross over, size and axis of the heart with a greater frequency than the static images and colour loops in all cases. In addition the real-time technique was able to demonstrate the pulmonary veins in 56% of cases compared with 3.6% for static images. The colour Doppler acquisition demonstrated blood flow through the atrial-ventricular and semi-lunar valves in 86% of cases.
Research Proposal

2.0 OBJECTIVES

The primary objectives of this research are 1) to test a standardized real-time acquisition technique for the detection of cardiac defects in routine sonographic screening of the fetus in the 2nd trimester and 2) to develop an image database of normal and abnormal fetal heart images for the purpose of training sonologists and sonographers to improve detection rates of congenital heart defects.

2.1 HYPOTHESES

1. During routine 2nd trimester screening, acquisition of cine-loops of the fetal heart will increase the detection rate of cardiac defects compared with reviewing static images.
2. Real-time assessment of fetal heart images will result in an improved rate of detection of cardiac defects by expert as well as novice image interpreters.
3. Using an image database training tool comprised of normal and abnormal fetal heart cine-loops will result in a measurable improvement in observer interpretation skill.

2.2 MILESTONES

To meet these objectives and test these hypotheses, milestones are identified: 1) The acquisition of normal and abnormal fetal cardiac images in the form of static images and cine-loops; 2) The development of an image database; 3) Review of the images to determine the rate of detection of cardiac defects by technique - static image vs. cine-loop; and 4) Training of year 3
radiology residents and year 3 sonography students to improve interpretation skills.

2.3 Study Population and Sample Size

The participants providing the normal fetal heart images will be selected from the low risk population scanned routinely in the radiology department at McMaster Children’s hospital. All patients with a normal sonogram will be included in the normal study population any patients with an abnormal sonogram will be excluded. The abnormal heart images will be acquired from the population of patients referred to the pediatric cardiology department. All patients with normal exams will be excluded from this group, only patients with abnormal heart exams will be included in this group.

The sample size was selected to include 14 patients with abnormal hearts and 79 patients with normal hearts. Based on the results of the pilot study conducted on 28 normal pregnancies, “Increasing the Detection Rate of Normal Fetal Cardiac Structures: A Real-Time Approach” (in press) it is expected that there will be a statistically significant difference in the detection rate of heart defects using the experimental method compared with the conventional technique.8

2.4 IMAGE ACQUISITION (4 Sonographers, 1 Pediatric Cardiologist and 1 PhD student)

The collection of images will be facilitated by Ted Scott, a PhD student who is also a Mohawk College instructor in the McMaster University-Mohawk College, collaborative Medical Radiation Sciences program. His experience includes design and delivery of courses in applied physics and instrumentation of sonographic systems, digital image management and applied cardiovascular physiology. In addition to his academic role he has extensive clinical experience and he has exercised leadership in the
national and provincial professional societies as a board member and committee organizer.

The Hamilton Health Sciences, radiology department at the McMaster University site will provide the opportunity to recruit 79 subjects participating in routine 2\textsuperscript{nd} trimester obstetrical screening. Consent from each subject will be obtained by the sonographer assigned to the patient and then each fetus will be scanned by the sonographer to acquire three conventional static images (protocol A) and two (four second) cine-loop sweeps through the heart (protocol B). These images will be acquired using at least 3 different sonographic systems (platforms). The images will be interpreted to verify normalcy and then will be exported from the Picture Archive Communication System (PACS) as anonymous DICOM images.

The Hamilton Health Sciences, pediatric cardiology department at the McMaster University site will provide the opportunity to recruit 14 subjects participating in the diagnosis of congenital heart defects. Consent from each subject will be obtained by the sonographer assigned to the patient and then each fetus will be scanned as above according to both protocols A and B by Dr. Mondal (pediatric cardiologist). These images will be acquired using at least one of the same sonographic systems (platform) as was used in the collection of normal images to ensure similarity of image presentation between the normal and abnormal categories. Each of these will diagnosed and categorized as individual cardiac defects. An array of different types of cardiac defects will be acquired in an effort to represent the different structural and functional effects they represent. Once the diagnosis is confirmed they will be exported from the PACS as anonymous DICOM images. Once these babies are born the diagnosis of the cardiac defects will be confirmed to validate the in utero diagnosis.
2.5 IMAGE DATABASE DEVELOPMENT (1 PhD Student)

Ted Scott (the graduate student) will collect the images acquired from the radiology and pediatric cardiology departments and import them into the Mohawk College MiniPACS, known as Xcelera. The Xcelera software and affiliated hardware provides the necessary tools to organize and store the images. The image reviewers will be able to assess the images using a standardized set of review tools including: adjustable cine-loop speed, frame by frame review, and limited grey-scale adjustment. Once developed, the database will be available for testing the hypotheses and skills training (see section 3.0 below).

2.6 IMAGE INTERPRETATION (2 Experts, 2 Non-experts)

The images will be reviewed by two experts as well as two novice interpreters. The reviewers will be given a brief orientation to the image database software and will assess all images blinded to each others results and to the actual diagnosis. The static and real-time images will be reviewed separately on different days to ensure that the interpretation of one set of images does not influence the interpretation of another. Within each group (real-time and static) the normal and abnormal cases will be randomly distributed. Each reviewer will be asked to identify five key anatomical structures: four chambers, the LVOT, the RVOT, the LVOT/RVOT crossover and cardiac situs/size. For each case the reviewers will be required to define the images as normal, abnormal or indeterminate. No attempt to identify the specific nature of a cardiac defect will be made. Once this data is collected it will be compared with the known standard obtained from the radiology and pediatric cardiology departments respectively. Using the diagnosis provided from the pediatric cardiology and radiology departments as a gold standard the sensitivity, specificity and accuracy of the respective techniques will be calculated. However validation of the normal radiology diagnosis will be completed as described in section 1.6 below to ensure the normalcy of the radiology diagnosis.
2.7 VALIDATION OF NORMAL IMAGES (2 Sonographers, 1 PhD Student)

The subjects recruited during their second trimester of pregnancy will be requested to return to the Mohawk College-McMaster University, Institute for Applied Health Sciences sonography laboratory once their babies are born, in the first 3 months of the post natal period. At this time, their babies will be scanned using a pediatric, three-dimensional sonographic system in an effort to validate the normalcy of their hearts. The babies will be scanned using a Philips Medical Systems, IU22 sonographic system and its two-dimensional matrix array transducer. The images will be analyzed using Q-Lab, a 3 dimensional image analysis software.

3.0 TRAINING

The development of an image database will provide the opportunity to train sonographers, radiology residents and sonography students to better detect abnormal hearts. At present the training for both these groups occurs within the Mohawk-McMaster Institute for Applied Health Sciences (IAHS). Ted Scott is responsible for leading a sonography seminar series for 3rd year residents in the McMaster University Radiology Residency program. He is also the sonography program co-coordinator for the collaborative Medical Radiation Sciences program between Mohawk College and McMaster University. In this role he will be able to use the data base as a training tool for 3rd year sonography students. Residents and sonography students will be given access to the images and asked to view the images and detect normal cardiac structures and determine which are abnormal. Their respective scores will be compared with their performance after a training exercise to determine the efficacy of the learning exercise. Further the imaging and assessment technique will be developed as a training course for local clinical facilities to be hosted at the
IAHS. In order to make this accessible to a wider audience it will be provided as a digital, multimedia program for use by sonographers and sonologists at distant sites in Canada and United States.

4.0 LIMITATIONS

Due to limitations in the number of cardiac defects included in the study it will only be possible to test the imaging technique across a representative sample of fetal cardiac defects. It will not be possible to evaluate the performance against all types of fetal cardiac defects. Due to limitations in the number of image reviewers, (2 expert and 2 non-expert) it will not be possible to test the technique across a wide array of potential interpreting physicians.

5.0 SIGNIFICANCE

Early detection of cardiac defects offers the obstetrician and delivery team the necessary time to schedule the delivery at an appropriate tertiary care center. Since all pregnant mothers are offered at least one sonogram and fetal cardiac defects occur with a frequency of nearly one in one-hundred pregnancies, the potential for improvement in the management of babies born with congenital heart defects is high. In addition, detection of a cardiac defect may signal the presence of other genetic anomalies such as Downs Syndrome. Identification of cardiac defects during pregnancy allows the parents to receive counseling and guidance to assist their decision making.
Reference:

*Diagnostic Ultrasound*, Rumack, C, Wilson, S, Charboneau, (3rd ed.), Elsevier Mosby, St.Louis Missouri, USA


5. ISUOG Education Committee, ‘Cardiac screening of the fetus: guidelines for performing the 'basic' and 'extended basic' cardiac scan’, *Ultrasound Obstet Gynecol*, vol. 27, pp. 107-113

6. Chaoui, R 2003, ‘The four chamber view: four reasons why it seems to fail in screening for cardiac abnormalities and suggestions to improve detection rate’, *Ultrasound Obstet Gynecol*, vol. 22, pp.3-10


Project #3, “Find it First”, proposal summary, protocol and sample size estimate

Study title:

Improving the ability of learners to identify congenital heart disease using a simulation based assessment in an online format, compared with traditional classroom instruction.

Abstract

The objective of the research is to demonstrate a more effective tool for students learning how to identify congenital heart disease. Using a randomized, two group experimental design, we will address the hypothesis: "Training students to use a simulation based standardized assessment technique online compared with traditional classroom instruction will increase their ability to identify congenital heart disease and increase their confidence and knowledge in assessment of the fetal heart."

The control group is defined as those students who receive four classroom lectures and related classroom learning activities. The time for instruction will be approximately 240 minutes and an allowance for independent study time of 90 minutes for a total of 330 minutes of time committed to learning.

The experimental group will receive approximately, 15 online tutorials amounting to 75 minutes of instruction and they will be performing 15 practice exercises online as formative assessment with feedback that will consume another 150 minutes. Total time committed to learning for this group will be 225 minutes.

Both groups will be evaluated on their ability to identify normal and abnormal structures using an electronic tool that will require students to review 25 cases of fetal cardiac anatomy. 10 of these cases will be abnormal and 15 will be normal, the sequence of the cases will be randomized. Students will identify 5 anatomic features for each case and determine that the case is either, normal,
abnormal or indeterminate. A normal result implies no further assessment, an abnormal determination will result in a referral to a pediatric cardiologist and an indeterminate finding will result in a follow-up reassessment in the obstetric screening centre. For each decision, the students will self-assess their level of confidence in the decision using a 10 point likert scale.

The null hypothesis, is the condition where no difference in student skills, knowledge or confidence is found between the two groups. The Chi Square test will be performed to evaluate the statistical significance of the results of the image analysis. Differences on the post-test evaluations will be tested using the T test for statistical significance.

Research Objectives

Students enrolled in the experimental protocol will be tutored in the use of a five step, 13 point inspection method for assessment of the fetal heart. These students will also be provided practice cases for each step of the technique and these will include immediate feedback. Students will be required to demonstrate mastery of each step before continuing to the next step of assessment. Three learning objectives are defined as follows:

4. Increased ability to identify normal fetal cardiac structures
5. Increased ability to identify abnormal fetal cardiac structures
6. Increased confidence and knowledge related to assessment of the fetal heart during routine obstetrical screening.

Significance

- Teaching and learning to assess the fetal heart during routine obstetrical screening is difficult
• Screening examinations should be sensitive and specific relative to the presence of disease
• Screening examinations must be conducted by non-experts to be effective
• Fetal cardiac structures are complex, small and rapidly moving
• Identification of abnormal structures requires a complete and systematic methodology in real-time to ensure a high yield of congenital heart disease during screening
• Current resources in this field are lacking in the area of training protocols and practice exercises
• Training of clinical sonographers has been demonstrated to resulted in substantial improvements in the yield of congenital heart disease during screening examinations

Outcome measures
• Improved scores in the knowledge of screening for CHD
• Increased rate of correctly identifying normal fetal heart structures
• Increased rate of identifying CHD and confidence level

Methods
• Classroom instruction, define common learning objectives for control group and experimental group
• Online learning, focus on five step, 12 point inspection with practice exercises for each step and examples of common pathologies
• Post-test will assess objective and subjective measures of knowledge and confidence
• A set of 25 cases will be used to quantitatively differentiate the detection rate of normal structures and CHD

Statistical methods, sample size
Sample size calculations for categorical and continuous data are provided below. A sample of 15 students in each group will provide
80% power and 5% significance level assuming a difference between groups of 0.5 using Chi Square analysis of correctly identified normal structures and CHD. The formula used is described below. The calculations were completed using the online statistical calculator provided by the Department of Obstetrics and Gynecology, The Chinese University of Hong Kong.

\[ n = \frac{Z_{\alpha}\sqrt{(1+1/m)p(1-p)} + Z_{\beta}\sqrt{p_0(1-p_0)/m + p_1(1-p_1)}}{(p_0 - p_1)^2} \]

\[ \bar{p} = \frac{p_0 + m \cdot p_1}{m + 1} \]

\[ n_c = \frac{n}{4 \left( 1 + \frac{1}{nm} \right)^2} \]

\( p_0 = \) Probability of event in Control Group
\( p_1 = \) Probability of event in Experimental Group
\( m = \) Ratio of controls to experiment subjects
\( n_c = \) Continuity correction factor

Reference:


The data collected from the multiple choice questions and likert scores will be statistically significant according to the sample size defined as 9 students in each group. This is sufficient to detect a difference of 0.2 between mean scores with a standard deviation = 0.15 providing a power value of 0.8 and statistical significance of .05.

The calculations were completed using the online statistics calculator, University of British Columbia

(http://stat.ubc.ca/~rollin/stats/ssize/n2.html)
Appendix B

Fetal Heart Sonographic Assessment Tool

This tool was developed in order to enable a completely electronic process for reviewing the static and real-time images of the fetal heart. The tool provided the image reviewers with a simple and effective method for scoring each set of images and coming to a decision of normal, abnormal or indeterminate status for the case. The tool facilitated data collection through a simple export function using a .CSV file to an excel data sheet. It also ensured that all reviewers shared a common experience and quality of review, standardizing the data analysis process.

Figure B-1

Log in screen, user identification and authentication page.
Application menu, links to the demonstration and image databases.

Figure B-3
The demonstration tutorial page for static images defines the image controls and navigation tools.
The demonstration tutorial page for cine-loop images defines the image controls and navigation tools.

Analysis page, allows the user to select anatomical status as normal, abnormal or not seen. These are then considered in making the decision of normal, abnormal or indeterminate for the case.
Figure B-6

Menu page, provides users access to the static image database, video database and demonstration tutorial.

Figure B-7

The anatomical reference points are visible in the header of this web page as a reminder for the image review. Scroll bar can be moved to scrub the frames.
Figure B- 8

The anatomical reference points are visible in the header of this web page as a reminder for the image review. The static image views can be toggled through all three frames, the four chamber view, the LVOT and RVOT views.
Appendix C

Find it First web application

The Find it First web application was developed to provide sonographers and interpreting physicians with the opportunity to learn a standardized assessment of the fetal heart in real-time. The tool employs tutorial based instruction, mastery learning and automated feed-back. This approach leverages a web based approach which makes the learning tool accessible to a global audience. Learners are able to practice each skill as many times as they need to in order to achieve mastery. The application can be accessed using the link provided below and the log in and password credentials that follow. Screen shots of many of the application’s key web pages are provided in figures below.

Link: http://rustynoob.com/FiF/

User identification: guest user

Password: finditfirst
Home

Welcome to the Find It First Website. Our goal here is assist in the education of students learning how to detect early heart defects in fetal infants through the use of neonograms. This website will train the students on what to look for and help them to recognize a abnormal heart in the fetus. We hope that with this training device more babies will be saved through early detection in the future.

Figure C-1

Landing page for the “Find it First” application.

Figure C-2

The introductory module provides a brief explanation of the objectives for the learning activities.
Figure C- 3

The second module uses a white board to define the embryological underpinnings of congenital heart disease.

Figure C- 4

This tutorial defines the first step in analyzing the fetal heart, the situs to four chamber sweep.
Figure C- 5
Each tutorial is followed by a series of 15-20 practice cases. Feedback is provided immediately. All practice cases must be successfully completed before moving to the next learning step.

Figure C- 6
Each module includes a tutorial that narrates the analysis of a number of abnormal cases. These cases provide the learner with examples that reinforce the screening methods.
After completing all five modules, the learner completes a final exam, including 25 clinical cases and eight multiple choice questions. Abnormal cases are randomly distributed.

In this sample case, all five attributes are scored and a final decision must be rendered before moving to the next case.
Figure C-9

A sample multiple choice question is displayed. The multiple choice questions are used to define basic skills.

Figure C-10

A user forum was developed to enable learners to draw upon their peers to address specific questions and issues that might arise from the learning activities.
Appendix D

Published papers

I have included three articles that I published in 2008 and 2013 respectively within this appendix. The following articles identified as numbers one and three are reprinted in whole or in part with permission from the Journal of Diagnostic Medical Sonography. Article number two was reprinted with permission from the American Institute of Ultrasound in Medicine.

1. “Increasing the Detection Rate of Normal Fetal Cardiac Structures: A Real-Time Approach.”
2. “Increasing the Detection Rate of Congenital Heart Disease During Routine Obstetric Screening using Cine Loop Sweeps.”
3. “Increasing Recognition of Fetal Heart Anatomy Using Online Tutorials and Mastery Learning Compared With Classroom Instructional Methods.”
Increasing the Detection Rate of Normal Fetal Cardiac Structures: A Real-Time Approach
Ted Scott, Hans Swan, Gerald Moran, Tapas Mondal, Judy Jones, Karm Guram and Jaime Huff
Journal of Diagnostic Medical Sonography 2008 24: 63 originally published online 21 February 2008
DOI: 10.1177/8756479308315234

The online version of this article can be found at:
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>> Version of Record - Mar 19, 2008
OnlineFirst Version of Record - Feb 21, 2008
What is This?
Increasing the Detection Rate of Normal Fetal Cardiac Structures: A Real-Time Approach

TED SCOTT, MAPSc, RDMS, RDMS, RVT
HANS SWAN, PhD
GERALD MORAN, PhD
TAPAS MONDAL, MD
JUDY JONES, BSc, RDMS, RDMS
KARM GURAM, MD
JAIME HUFF, BSc, RDMS

The purpose of this study was to determine if acquiring real-time sweeps of the fetal heart would be a more effective method of identifying normal cardiac structures compared with using static images during routine second-trimester obstetric sonograms. Subjects were scanned using three different techniques. The static image acquisition (protocol A) included three images of the fetal heart. Protocol B used two gray-scale sweeps through the fetal heart. Protocol C acquired three color loops of the fetal heart. The sweeps demonstrated a complete normal cardiac assessment in 71% of studies, compared with the static image and color Doppler techniques that completed a normal cardiac assessment in only 39% of studies, respectively. The real-time technique detected four chambers, the left ventricular outflow tract (LVOT), the right ventricular outflow tract (RVOT), the LVOT/RVOT crossover, and size and axis of the heart with a greater frequency than the static images and color loops in all cases. In addition, the real-time technique was able to demonstrate the pulmonary veins in 56% of cases compared with 3.6% for static images. The color Doppler acquisition demonstrated blood flow through the atrial-ventricular and semilunar valves in 86% of cases.

Key words: sonography, fetal heart, real-time, static, detection, tissue harmonic

The use of sonographic imaging for routine fetal screening in the second trimester has been adopted by the Canadian health care system and a number of European countries as a standard of care. According to a survey of 2758 referrals to the fetal cardiology unit at Guy’s Hospital,
London, UK, the low-risk population for congenital heart defects is the source of 80% of congenital heart defects. This fact underscores the importance of routine screening for detecting congenital heart defects. Routine screening provides a more accurate measure of gestational age and earlier detection of multiple pregnancies, and it may detect congenital malformations. The Eurofetus study identified marked differences in sensitivity for the detection of different malformations. Abnormalities of the urinary system and nervous system were most easily detected with a sensitivity of 88.5% and 88.3%, respectively. In this study, cardiac abnormalities were not well detected; sensitivity for major cardiac defects was 38.8% and minor defects 20.8%. In Canada, an obstetric screening examination is performed in real time and documented as a series of still images archived electronically or on film. The interpretation of the cardiac images is performed by a radiologist or obstetrician using the still images. Present detection rates for congenital heart defects (CHD) vary widely depending on a number of factors: operator skills, maternal obesity, fetal position, inadequate image optimization, and visualization of the four-chamber view only. The American College of Radiology (ACR) and the International Society of Ultrasound in Obstetrics & Gynecology (ISUOG) have published guidelines for routine second-trimester screening that require the four-chamber view and, where possible, views of the left ventricular outflow tract (LVOT) and right ventricular outflow tract (RVOT) to address this limitation.

Acquisition of static images of the fetal heart provides a very limited quantity of diagnostic information; the identification of normal cardiac structures cannot be completely demonstrated as a series of a few static slice images. The interpretation of key structural relationships can be completed only during a real-time interrogation. In practice, the detection of the critical normal structures is accomplished solely by the sonographer. This approach limits the interpreter’s ability to confirm the findings of the sonographer. The main objective of this pilot study is to demonstrate that acquiring real-time loops of the fetal heart can be accomplished with minimal additional acquisition time and skill. In addition, the static and real-time techniques are compared in an effort to demonstrate the additional anatomical information that is accessible using a real-time acquisition.

The real-time loops will add considerable diagnostic value to the screening process because two interpretations will be performed on every examination: the preliminary review by the sonographer and the summary review by the sonologist. Another advantage of using the real-time loops is the opportunity it provides the sonologist to review the images repeatedly in real time and evaluate structures at different points during the cardiac cycle. The ability to assess structures during the diastolic phase has been found by Chaoui to be helpful in detecting atrial-ventricular septal defects. Furthermore, it is well established that observation of moving structures provides a more sensitive means of detecting small differences in form. A cine loop of a sweep through the cardiac outflow tracts will allow the sonologist to better appreciate the relationship between the LVOT and RVOT, which is crucial for ruling out congenital abnormalities. Hosono et al found the use of tissue harmonic imaging (THI) to be advantageous in imaging fetal cardiac tumors because of improvements in image contrast. Using THI will improve the quality of the images and may influence the detection rate of cardiac structures as well.

Acquisition of real-time loops assumes that the sonography systems that are used are capable of storing and transmitting real-time loops to a network. A survey of 21 local screening centers illustrated in Table 1 found that 95% of centers acquired and stored images electronically using a Picture Archiving Communications System (PACS). Most centers acquired three static images of the fetal heart: the four-chamber view and the LVOT and RVOT view (see Table 1). For the purpose of this pilot study, this combination of static images represents the conventional technique, protocol A.

**Research Question/Objectives**

This study compared static and real-time imaging techniques applied to the assessment of the fetal heart in routine screening.
RESEARCH AIMS

- Demonstrate the ability to acquire the experimental protocol B in less than five minutes
- Demonstrate an increased rate of detection of cardiac structures using real-time compared with static images

Method

The research protocol was reviewed and approved for use by the ethics committee of Charles Sturt University ( Wagga Wagga, NSW, Australia) and the ethics committee of Mohawk College (Hamilton, Ontario, Canada). Exclusion criteria included a family history of congenital heart defects or an abnormal second-trimester obstetric sonogram. All 28 subjects had a normal second-trimester sonogram prior to participation in this study. Images were acquired using the Philips Medical Systems (Bothell, Washington) HDI 5000 and Envisor sonography systems. Images were acquired using a curvilinear array transducer with a fetal cardiac preset using tissue harmonic image processing.

Subjects were scanned using three different techniques. The static image acquisition, protocol A, acquired three images of the fetal heart: the four chamber view, the LVOT view, and the RVOT view (see Figures 1–3). The real-time sweep, protocol B, acquired two gray-scale sweeps of four seconds’ duration each through the fetal heart. The first sweep began at the level of the transverse abdominal circumference with a visible stomach and swept into the transverse four-chamber view. The second sweep began at the four-chamber view and swept through the LVOT and RVOT (see Figures 4–7). Using protocol C, three real-time color cine loops of four seconds’ duration were...
acquired. The first was a sweep from the level of the transverse abdominal circumference with a visible stomach into the transverse four-chamber view. The second sweep began at the four-chamber view and swept through the LVOT and RVOT. The third was a color cine loop of the three-vessel view.

Informed consent was obtained, and then subjects were randomly assigned a sonographer who completed protocol A, B, or C. Five sonographers acquired images for this project. All sonographers had a minimum of three years’ experience in obstetrical sonography and were credentialed as RDMS (obstetrics and gynecology) by the American Registry of Diagnostic Medical Sonographers (ARDMS). The sonographer recorded the scan time for the acquisition using an electronic timer. Every subject was scanned by at least two different sonographers. Images were acquired and stored on the Philips Medical Systems Xcelera Minipacs. No additional training was provided to save the real-time loops compared with the static images. Sonographers were limited to a maximum of ten minutes to complete each protocol in an effort to replicate the practical limitations of the clinical environment.

The image sequences acquired were reviewed independently by two different fetal cardiac sonography experts blinded to each other’s results. The reviewers are experts in acquiring and interpreting fetal cardiac sonograms. The first was a sonographer (JJ) with 16 years of pediatric cardiac experience registered with RDCS (pediatric and fetal echo) credentials, and the second was a pediatric cardiologist (TM). In addition to the expert reviewers, two nonexperts reviewed the images independently and were blinded to each other’s results. The first was a radiology resident in year three of his training (KG), and the second was a cardiac...
FIGURE 7. Right ventricular outflow tract (RVOT) view from real-time sweep 2.

TABLE 2.
Subject Characteristics and Protocol Acquisition Times

<table>
<thead>
<tr>
<th>Subjects (N = 28)</th>
<th>Average</th>
<th>95% Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gestational age</td>
<td>27 weeks 24 weeks, 5 days</td>
<td></td>
</tr>
<tr>
<td>0 days</td>
<td>28 weeks, 6 days</td>
<td></td>
</tr>
<tr>
<td>Maternal body</td>
<td>27.8</td>
<td>25.8–29.8</td>
</tr>
<tr>
<td>mass index</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maternal body</td>
<td>1.8</td>
<td>1.6–1.9</td>
</tr>
<tr>
<td>wall, cm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acquisition time, protocol A (00:00)</td>
<td>3.49</td>
<td>2.39–4.58</td>
</tr>
<tr>
<td>Acquisition time, protocol B (00:00)</td>
<td>4.18</td>
<td>3.19–5.17</td>
</tr>
<tr>
<td>Acquisition time, protocol C (00:00)</td>
<td>6.32</td>
<td>5.14–7.51</td>
</tr>
</tbody>
</table>

sonographer (JH) with RDCS credentials and less than one year of experience in performing fetal cardiac studies. Each observer recorded the detection of five cardiac structures as detected = 1 or missed = 0 (see Table 3). A complete normal assessment requires a score of 5, and an incomplete assessment is recorded as any total less than 5.

STATISTICAL ANALYSIS

Interobserver differences were tested using a kappa score for agreement between detection of structures. A one-way analysis of variance (ANOVA) was performed to test for agreement between the means of total detection rate scores and the means of the acquisition times. Detection rate differences for complete and incomplete assessments were analyzed using the McNemar chi-square test.

Results

The subjects average gestational age was 27 weeks, 0 days, with an average body mass index (BMI) of 27.8 and an average body wall thickness of 1.8 cm (see Table 2). The acquisition time for the static images (protocol A) is statistically equivalent to the acquisition time for protocol B, and the mean time for both was less than five minutes (see Table 2). The acquisition of protocol C exceeded five minutes, with a mean time of 6:32, which is statistically different from protocols A and B. Interobserver agreement for the detection of cardiac structures using static images ranged from fair to excellent using kappa scores. Interobserver agreement for the detection of cardiac structures using real-time images ranged from excellent to poor using kappa scores.

DETECTION RATES

The real-time image loops were found to have the highest detection rates for all anatomic structures compared with the static images and color loops (see Table 3). The four-chamber view was identified in 100% of all real-time loops and in only 68% of static images and 84% of color loops. The LVOT and RVOT crossovers was detected in 73% of real-time loops and only 47% of static images. Similar differences were found for the LVOT and RVOT as individual structures.

Using the static images, 39% of studies generated a score of 5 for complete assessment compared with the real-time technique, which was able to completely assess the normal structures in 71% of studies. This generated a statistically significant difference between proportions of 0.321 (P = .0352) using the McNemar chi-square test.

The color Doppler loops provided a complete assessment in only 39% of cases. The color Doppler loops did provide the ability to assess the blood flow through the atrial-ventricular valves and semilunar valves in most cases, and this represents additional diagnostic information compared
TABLE 3.
Rate of Detection of Cardiac Structures by Technique (in Percentages)

<table>
<thead>
<tr>
<th>Expert (N = 28)</th>
<th>Four Chamber</th>
<th>LVOT</th>
<th>RVOT</th>
<th>RVOT/LVOT Crossover</th>
<th>Axis and Size</th>
<th>Complete Examination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static</td>
<td>68</td>
<td>64</td>
<td>64</td>
<td>47</td>
<td>93</td>
<td>39</td>
</tr>
<tr>
<td>Color Doppler loops</td>
<td>84</td>
<td>82</td>
<td>79</td>
<td>73</td>
<td>93</td>
<td>39</td>
</tr>
<tr>
<td>Gray-scale loops</td>
<td>100</td>
<td>86</td>
<td>81</td>
<td>73</td>
<td>100</td>
<td>71</td>
</tr>
</tbody>
</table>

LVOT, left ventricular outflow tract; RVOT, right ventricular outflow tract.

TABLE 4.
Detection Rate of Color Flow Using Color Doppler Loops by View (in Percentages)

<table>
<thead>
<tr>
<th>Expert (N = 28)</th>
<th>Four Chamber</th>
<th>Five Chamber</th>
<th>Three-Vessel View</th>
<th>Assessment of Valves for Regurgitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Color Doppler loops</td>
<td>91</td>
<td>84</td>
<td>45</td>
<td>86</td>
</tr>
</tbody>
</table>

TABLE 5.
Detection Rate Differences Between Experts and Nonexperts (in Percentages)

<table>
<thead>
<tr>
<th>Expert/Nonexpert Difference</th>
<th>Four Chamber</th>
<th>LVOT</th>
<th>RVOT</th>
<th>RVOT/LVOT Crossover</th>
<th>Axis and Size</th>
<th>Complete Examination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static</td>
<td>0</td>
<td>13</td>
<td>4</td>
<td>8</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>Color Doppler loops</td>
<td>11</td>
<td>4</td>
<td>0</td>
<td>7</td>
<td>2</td>
<td>28</td>
</tr>
<tr>
<td>Gray-scale loops</td>
<td>14</td>
<td>4</td>
<td>3</td>
<td>5</td>
<td>2</td>
<td>15</td>
</tr>
</tbody>
</table>

LVOT, left ventricular outflow tract; RVOT, right ventricular outflow tract.

with the gray-scale static and real-time loops. The color Doppler loops were able to assess the four-chamber view and five-chamber view in most cases. The three-vessel view was achieved only in 45% of cases (see Table 4).

EXPERT/NONEXPERT DIFFERENCES

The expert reviewers and nonexpert reviewers agreed closely in their assessment of static images. The largest difference between these groups was in the evaluation of the LVOT, with a difference of 13% between groups (see Table 5). All other structures differed by less than 10%, respectively. There was close agreement between the experts and nonexperts interpreting the gray-scale and color loops, with the exception of the four-chamber view, in which the gray-scale loop differed by 14% and the color loop differed by 11%. Assessment of a complete examination was in close agreement between experts and nonexperts for the static images, with a greater difference of 15% and 28% (see Table 5) with the gray-scale and color loops, respectively.

SAMPLE IMAGES

The static image of the four-chamber view allows the observer to distinguish the axis, size, and left/right chambers under ideal conditions (see Figure 1). The static images of the LVOT and RVOT (see Figures 2 and 3) will describe continuity between the outflow tracts and the corresponding chambers under ideal conditions. The static images cannot effectively assess the cardiac valves or cardiac motion.

Static images have been extracted from the real-time loops in an attempt to demonstrate the added value that loops provide. The first sweep begins at the transverse abdominal circumference (see Figure 4). The four-chamber view is visualized next in Figure 5. The second sweep demonstrates...
the LVOT in Figure 6, and the RVOT is visualized in Figure 7. In addition, the real-time sweeps provided continuity between the stomach and abdominal circumference in 100% of real-time studies. One or more pulmonary veins were visualized as contiguous structures with the left atrium in 56% of real-time cases compared with 3.6% of cases with static images (see Figure 8). A color image extracted from a sweep from the abdominal circumference to the four-chamber view demonstrated blood flow through the atrial-ventricular valves in Figure 9. The blood flow through the LVOT is evident (see Figure 10) as an image acquired during the sweep from the four-chamber through the outflow tracts. In Figure 11, the great vessels demonstrate antegrade blood flow in a three-vessel view.

**Discussion**

The subjects were a representative sample of expectant mothers in the late second and early third trimesters. The requirement of a normal diagnostic second-trimester sonogram result as a prerequisite for participation in this study resulted in the mean gestational age of 27 weeks, 0 days. The gray-scale, real-time sweeps were acquired as quickly as the static images, and very little additional expertise was required to capture the real-time loops.
The structure of the heart is complex, and relationships and continuity between structures such as the crossover of the outflow tracts are critical for determining normalcy. Three static views of the four-chamber and outflow tracts are inadequate for complete assessment in most cases. Static images are much less likely to be able to demonstrate subtle anatomic structures such as the moderator band and atrioventricular valve offset, which are useful for distinguishing the left and right chambers. Static images cannot assess the valves and their motion effectively, and this limits observer confidence in detecting the outflow tracts and their relationship. The real-time loops are able to detect these subtle anatomic structures and their motion; this fact is reflected in the ability of the real-time loops to detect a complete normal heart in 71% of studies compared with 39% of static studies. In addition to the identification of the four-chamber and outflow tracts, the real-time sweeps provided the continuity of the left-sided stomach in the abdomen as the sweep translates from the abdomen to the chest in 100% of cases.

In a few cases, the relationship between the outflow tracts could not be established in static images or real time at normal speed, but using a frame-by-frame analysis, we were able to establish that relationship. This affirms the value of acquiring loops of information rather than individual slices as well as the need to reevaluate the heart in real time after the image acquisition process.

The color Doppler loops provided useful blood flow information in most cases, but this advantage was limited to some degree by the fact that color blooming had the effect of obscuring part of the anatomy represented in gray scale. Unfortunately, our PACS and sonography systems did not permit the suppression of color. Another drawback to the color Doppler was the need for additional operator expertise to fine-tune the color velocity scale or pulse repetition frequency (PRF) and color gain. The three-vessel view was detected in only 45% of cases compared with 91% and 84% of cases for the four-chamber and five-chamber views, respectively. This difference most likely reflects the relative difficulty in acquiring the three-vessel view compared with the four-chamber and five-chamber views.

It is interesting to note that in nearly all cases, there were only minor differences in the detection rates between the expert image reviewers and non-expert reviewers. Review of the static images resulted in the least difference between these groups, likely due to the fact that reviewers assessed only one image/view in comparison with the real-time loops that generated a series of 120 images from a four-second acquisition. The cine loops provided the reviewers with so much additional information that it had the effect of introducing a wider range of interpretation. On the basis of these findings, it is clear that the identification of the four chambers, outflow tracts, outflow tract crossover, situs, and location can be achieved consistently by experts and nonexperts.

**REAL-TIME METHODOLOGY**

Typically, second-trimester screening examinations are scheduled for approximately 30 minutes, in which time the sonographer is obliged to interrogate the maternal pelvic and fetal anatomy, as well as acquire representative images and measurements to estimate gestational age. Fetal cardiac anatomy, owing to its complex shape and rapid movement, represents the sonographer's greatest diagnostic challenge compared with static fetal anatomical structures such as the brain or abdominal organs. Given these constraints, a robust screening technique needs to be able to provide the maximum relevant anatomical information with the minimum operator skill and time. For most screening centers, a reasonable goal would be to identify an abnormal heart and refer the patient to a pediatric cardiology laboratory to diagnose the specific nature of the defect. The use of color Doppler cine loops did provide additional blood flow information in most cases, but this advantage was offset by the additional time required to acquire these loops, the additional operator skill that is needed to apply color Doppler effectively, and the fact that the color may obscure visualization of some gray-scale anatomy unless it is suppressed. For these reasons, it is proposed that the two-sweep cine loop acquisition technique tested in this study be used for assessing the fetal heart in the second trimester. Applying this method of acquisition
will allow the image interpreter to identify the key cardiac anatomical landmarks and relationships that were assessed in this study in most cases. This method will provide the most effective assessment of fetal cardiac anatomy with minimal additional time and skill.

**STUDY LIMITATIONS**

It was not possible to blind the observer to the techniques used for acquisition because a static image is inherently different from a real-time loop. The manipulation of the real-time loops as a frame-by-frame analysis was left to the discretion of the individual reviewers. Although this may have limited the standardization of the image presentation, the manipulation of frame rate by the user is a key advantage of the technique.

**Conclusion**

Real-time sweeps through the fetal heart are easily and rapidly acquired with minimal additional operator skill. Acquiring four-second, real-time loops provides the sonologist with the information required to more effectively assess the fetal heart. Real-time sweep acquisitions of fetal cardiac structures are much more effective in completing a normal assessment. This study was able to demonstrate a complete cardiac assessment in 71% of studies using a real-time acquisition technique compared with 39% of static image acquisitions. The use of color Doppler provided blood flow information of the atrial-ventricular valves in 86% of subjects. A standardized two-sweep acquisition through the fetal heart can be acquired quickly and with minimal additional operator skill. In the future, studies comparing the performance of this technique between normal and abnormal fetal hearts will be needed to demonstrate the clinical value of real-time loops for detecting congenital heart disease.

**Acknowledgments**

This project was undertaken with the financial support of the SDMS Education Foundation, Graduate Research Award, and the Bracco Diagnostics Research Award. Thanks are given to the following sonographers: Malka Glasner, Mandie Bird, Rob Nottle, and Melissa Wood for their efforts in acquiring the fetal cardiac images. The authors also thank Philips Medical Systems, Canada, and Mohawk College for their support of this project. Equipment was provided by Philips Medical Systems, Canada, and laboratory space was allotted by Diane Barrafiato, associate dean, Medical Radiation Sciences, School of Health Sciences, Mohawk College.

**References**

Increasing the Detection Rate of Congenital Heart Disease During Routine Obstetric Screening Using Cine Loop Sweeps

Ted E. Scott, MApSci, Judy Jones, BSc, RDMS, RDCS, Herschel Rosenberg, MD, Andrea Thomson, MD, Hournaz Ghandehari, MD, Neil Rosta, MD, Kim Jozkow, BSc, RDCS, RDMS, RVT, Malka Stromer, MED, BSc, RDMS, RVT, Hans Swan, PhD

Objectives—The purpose of this study was to demonstrate an increase in the detection rate of fetal cardiac defects using 2 cine loop sweeps.

Methods—Image reviewers examined a series of 93 cases randomly sorted, including 79 studies with normal findings and 14 studies with abnormal findings. All of the images were assessed by 5 standard criteria. Cases were classified as normal, abnormal, or indeterminate. Reviewers using the conventional approach reviewed 3 still images: the 4-chamber, left ventricular outflow tract, and right ventricular outflow tract views. Reviewers using the cine loop sweeps viewed 2 grayscale sweeps through the fetal heart in real time. The image sequences were reviewed independently by 2 experts, 3 nonexperts, and 2 sonographers blinded to each others’ results.

Results—The cine loop sweeps had an increased detection rate of 38% for the nonexperts and 36% for the experts compared with the conventional approach. The cine loop sweeps allowed identification of all cardiac defects by at least 2 of the 7 reviewers; the percentage of cases with false-positive findings was 3.9%. With the conventional approach, 2 defects went undetected by all reviewers, and 4 defects were found by only 1 reviewer; the percentage of cases with false-positive findings was 5.4%.

Conclusions—The use of cine loop sweeps has the potential to increase the detection of fetal cardiac defects without increasing the rate of false-positive findings or increasing the interpretation and decision-making times.

Key Words—cine loop; congenital heart disease; prenatal; real time; screening; sonography; sweeps

Most deaths from congenital defects in childhood can be attributed to congenital heart disease.1 The most common cause of birth defects, congenital heart disease, is most frequently reported, with an incidence of 0.8% of all live births.2 The prenatal diagnosis of congenital heart disease can improve clinical outcomes of those affected after birth.3–6 Prenatal diagnosis of congenital heart disease is critically important to ensure optimal management of the pregnancy, optimal delivery of the neonate, and provision of support for parental decision making. In addition, those at high risk for congenital heart disease may be relieved of additional anxiety and fears due to the possibility of congenital heart disease by confirmation of normality.7
Prenatal screening performance has been documented in the literature extensively over the past 25 years, and although the reports vary in study design, they consistently demonstrate poor performance in the low-risk population using a 4-chamber assessment, with detection rates ranging from 5% to 48%.8–10 More recently in a number of prospective studies that included the outflow tracts and additional operator training, some improvements have been observed, with sensitivities ranging from 57% to 78%.1,10,11

Although the inclusion of outflow tracts as an extension to a basic examination of the 4 chambers has provided encouraging results, further improvements in screening protocols are needed. The interpretation of still images of the heart used by most routine obstetric screening centers is a considerable barrier to detection of congenital heart disease.12 In some instances, identification of congenital heart disease, such as an atrioventricular septal defect, is increased by assessing the 4-chamber view during the diastolic and systolic phases of the cardiac cycle.12,13 Reliance on still images only for interpretation assumes that the sonographer will recognize congenital heart disease in the course of a real-time assessment of the fetal heart and record an image that clearly depicts the disease. In the event that the sonographer misses the presence of congenital heart disease, it is unlikely that the disease will be shown on the still images. However, several alternatives are available to interpreting physicians. Moving 3-dimensional images of the fetal heart can be stored for review and interpretation using spatiotemporal image correlation technology.12,13 Three-dimensional imaging has the potential to improve the detection rate of congenital heart disease because it provides unlimited opportunities to review the fetal heart in motion either as a volume or as a cine loop of slices.14 Acquisition of 3-dimensional volumes of the fetal heart requires additional training and resources.12 The need for additional investments in training and equipment may explain why 3-dimensional assessment of the fetal heart has not become a standard practice in routine obstetric screening.

The use of cine loop sweeps to assess the fetal heart has been recommended as a practical means of increasing the detection rate of congenital heart disease.12 Acquiring cine loop sweeps through the fetal heart is a simpler alternative compared with acquiring 3-dimensional images. McGahan et al15 recommended the use of cine loop sweeps to examine the crisscross of the outflow tracts in an effort to increase the likelihood of detecting conotruncal defects. No new equipment is required other than the storage capacity to store cine loops within the imaging facility. Very little additional sonographer training is needed because the sweeps can be incorporated into existing imaging protocols with little effort. Our approach includes 4 of the 5 short-axis views described by Yagel et al.16 To minimize additional sonographer training, we did not include the 3-vessel view, described as the fifth short-axis view. The first cine loop sweep begins at the level of the stomach in the transverse plane and moves superiority to the 4-chamber view. The second sweep begins at the 4-chamber view in the transverse plane and sweeps upward to include the outflow tracts. The objective of this study was to determine whether using 2 cine loop sweeps would improve the detection of congenital heart disease compared with still images.

**Materials and Methods**

**Patients**

This study was approved by the Charles Sturt University Ethics in Human Research Committee, Hamilton Health Sciences/Faculty of Health Sciences Research Ethics Board, and Grey Bruce Health Sciences Research Ethics Board. Informed parental consent was obtained for every case. Normal images including still images and cine loop sweeps of the fetal heart from 79 expectant mothers during the course of their routine second-trimester screening sonographic examinations were obtained. Still images and cine loop sweeps of the fetal heart from 14 expectant mothers referred to the McMaster Children’s Hospital pediatric cardiology laboratory for follow-up of suspected congenital heart defects were also gathered, and their diagnoses were confirmed by postnatal examinations; the neonates were not followed (Table 1).

**Image Acquisition**

In an effort to ensure a realistic evaluation of this approach, images were acquired with a variety of ultrasound equipment and transducers from different manufacturers, including Toshiba America Medical Systems, Inc (Tustin, CA), 4.0- and 5.0-MHz curvilinear transducers; Philips Healthcare (Bothell, WA), 5–1-MHz curvilinear transducer; GE Healthcare (Waukesha, WI), 4–8-MHz curvilinear transducer; and Siemens Medical Solutions (Malvern, PA), 6–2-MHz curvilinear transducer. Equipment settings were optimized to include a high frame rate and harmonic imaging.

For both normal and abnormal cases, 3 still images and 2 cine loop sweeps were acquired. The still images included the 4-chamber view, the left ventricular outflow tract (LVOT) view, and the right ventricular outflow tract (RVOT) view. These images represented a conventional approach to image acquisition. With the same equipment settings used in the conventional method and, when possible, the same acoustic window and fetal position, 2 cine...
loop sweeps were acquired. Each cine loop sweep was acquired with a 4-second electronic capture stored to a local hard disk. The first cine loop sweep is described as the situs–4-chamber sweep (Video 1). The technique used is described as follows: In a transverse abdominal section, the transducer is moved cephalad from the abdominal circumference into the 4-chamber view, without changing angles to the fetus (Figure 1). Acquisition of the image should begin showing the situs, capture at least 2 beats of the situs to allow the interpreting physician to appreciate the pulsatility of the aorta, and then slowly slide the transducer cephalad without changing the angle. The acquisition should then end after at least 2 beats of the 4 chambers has been shown. The second cine loop sweep is described as the 4-chamber–outflow sweep (Video 2). To acquire this cine loop sweep, we used the following technique: From the 4-chamber view, rotate the transducer slightly toward the left fetal shoulder and angle cephalad; the first outflow visible is the LVOT/aorta. Angle the transducer more cephalad to visualize the RVOT/pulmonary artery.

**Image Review**

Both abnormal and normal images were collated into an image data set representing 79 normal and 14 abnormal cases, totaling 93 distinct pregnancies. An online computer-generated randomizer (www.random.org) was used to compile these image data sets in random order. There were 7 image reviewers divided into 3 classes: expert, nonexpert, and sonographer. There were 2 experts, a pediatric cardiologist with more than 10 years of clinical experience (expert 2) and a pediatric cardiac sonographer with more than 10 years of experience (expert 1); 3 nonexpert radiologists (nonexperts 1–3), and 2 sonographers each with more than 5 years of experience (sonographers 1 and 2). Each of the image reviewers, blinded to one another’s results, worked through the 93 sets of still images sequentially using the same randomized series. On completion of their review and interpretation of these, they went on to review and interpret the 93 sets of the situs–4-chamber and 4-chamber–outflow cine loop sweeps. Their image review was enabled by the use of a software program, the Fetal Heart Sonographic Assessment Tool (Figure 2). This software allowed them to electronically record their decisions using an electronic checklist and assess 5 key points to show normalcy; (1) situs, position, and size; (2) 4-chamber morphologic characteristics; (3) LVOT-chamber contiguity; (4) RVOT-chamber contiguity; and (5) LVOT-RVOT relationship.

A second electronic record was made to determine 1 of 3 outcomes: normal, abnormal, or indeterminate. To set a level decision-making process, each reviewer was advised that a normal decision would imply no further

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>n</th>
<th>Gestational Age, wk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hypoplastic left heart</td>
<td>4</td>
<td>19–22</td>
</tr>
<tr>
<td>Hypoplastic left heart and atrioventricular septal defect</td>
<td>1</td>
<td>21</td>
</tr>
<tr>
<td>Atrioventricular septal defect</td>
<td>3</td>
<td>18–22</td>
</tr>
<tr>
<td>Large heart</td>
<td>1</td>
<td>21</td>
</tr>
<tr>
<td>Rhabdomyoma</td>
<td>1</td>
<td>26</td>
</tr>
<tr>
<td>Double-outlet right ventricle with pulmonary stenosis</td>
<td>1</td>
<td>24</td>
</tr>
<tr>
<td>Supraventricular tachycardia</td>
<td>1</td>
<td>32</td>
</tr>
<tr>
<td>Double-outlet right ventricle with tetralogy spectrum</td>
<td>1</td>
<td>19</td>
</tr>
<tr>
<td>Tetralogy of Fallot</td>
<td>1</td>
<td>2nd trimester</td>
</tr>
</tbody>
</table>
imaging or follow-up; an indeterminate decision would imply follow-up sonography; and an abnormal decision would be referred to the pediatric cardiology laboratory for further examination.

Statistical Analysis
The statistical significance of the detection rates provided by the image reviewers was determined with the McNemar $\chi^2$ test for a difference of proportions with a significance level of $P < .001$. All other data were analyzed with a 1-way analysis of variance. The analysis was performed with Analyse-it software (Analyse-it Software, Ltd, Leeds, England).

Results
Expert reviewer 1 detected 50% of the congenital heart diseases using the still images and detected all but 1 of them using the cine loop sweeps (Table 2). The detection rates varied most within the cine loop sweeps in both the expert and nonexpert groups. Here, the detection rates varied by 29% and 28%, respectively. The greatest improvement in detection between assessment methods was found in the nonexpert group (nonexpert 3), with an improvement of 64%; the least improvement was found in the sonographer group (sonographer 2), with no difference observed. For all other reviewers, the detection rates improved from 7% to 64%.

The experts detected the most congenital heart diseases, with average rates of 43% for the still images and 79% for the cine loop sweeps (Table 3). The nonexpert group identified on average only 14% of congenital heart diseases using the still images and 52% using the cine loop sweeps. The sonographers identified only 18% using the still images and had nearly the same detection rate, 21%, for the cine loop sweeps. The number of cases with false-positive findings identified overall by the image reviewers was quite low, with an average of 5.4% observed in the still image review compared with 3.9% for the cine loop sweeps.

Discussion
The analysis of the cine loop sweeps resulted in improved detection rates compared with the still images for experts and nonexperts of 36% and 38%, respectively. The nearly equivalent rates of improvement found in both groups suggest that the value of the cine loop sweeps is equally applicable to expert and nonexpert interpreting physicians. Within the nonexpert group, the variations in detection rates were 14% for the still image review and 28% for the cine loop sweeps. This pattern of increased variation in detection rates for the cine loop sweeps was also observed in the expert group. In this group, the variation in detection rates for the still image review was 14%, and the variation for the cine loop sweeps was 29%. The increased variation between the reviewers may be explained by the fact that the cine loop sweeps provided considerably more image information for analysis, allowing individual interpretive skills to be demonstrated to a greater degree than for the still images. The detection rate for the nonexpert reviewers using the still images was only 14%. This result is in alignment with the reality that the still images of the 4-chamber and outflow tract views provide a very minimal amount of diagnostic information to the interpreting physician during the image review process. However, the expert reviewers were able to identify 43% of congenital heart diseases using the same still images while maintaining a low rate of false-positive identification. This difference suggests that the...
importance of training and experience can have a substantial impact on the detection rate of congenital heart disease.

Surprisingly, the sonographers’ improvement in the detection rate using the cine loop sweeps compared with the still images was only 3%, and this finding was not consistent with that of the expert and nonexpert results. The sonographers’ detection rates overall were low: 21% for the cine loop sweeps and 18% for the still images. Compared with the performance of the experts and nonexperts, these low detection rates suggest that the interpretative expertise of the sonographers was not as refined as that of the physicians. This finding was not surprising because the role of a sonographer is primarily image acquisition, initial review, and interpretation, whereas the interpreting physician’s role is primarily analysis and interpretation. The training and experiences for each of these health care professionals reflect these differences in roles.

These results indicate that it is essential that the interpreting physician have access to real-time sweeps of the heart if the goal is to detect congenital heart disease in routine obstetric screening. Furthermore, the cine loop sweeps can be shared electronically via a secure network connection should the interpreting physician request expert consultation.

The average rates of false-positive identification of congenital heart disease for all reviewers were 5.4% for the still images and 3.9% for the cine loop sweeps. This finding suggests that the reviewers understood the potential emotional impact and stress that a positive finding would have on the parents and families affected, and they set a relatively high threshold for a positive finding. This factor might help explain why the expert and nonexpert detection rates did not exceed 80% even with the use of cine loop sweeps.

All 14 abnormal cases were identified on the cine loop sweeps, and 2 cases, a large heart and a hypoplastic left heart, were identified by all 7 reviewers. In contrast, 2 cases, an atrioventricular septal defect and a double-outlet right ventricle with tetralogy spectrum, were missed by all 7 reviewers using the still images. An example is described below in which the still images provided a false impression of normalcy compared with the cine loop sweeps. To illustrate this example, a frame was grabbed from the cine loop sweep on a Twoflower 2.0.3 VLC media player (VideoLAN Organization, Paris, France) to show the abnormality.

In Figure 3, a normal-looking 4-chamber view is contrasted with a more abnormal-looking view extracted from the cine loop sweep. This was confirmed as tetralogy of Fallot. Only 1 of the 7 reviewers identified this abnormality on the still images. These findings further express the need for an assessment in real time.

Although the results of this study uniformly point toward the increased value of the cine loop sweeps compared with the still images, because of the relatively small sample of 14 cardiac defects, statistical significance was achieved in the results for only 2 of the 7 reviewers. Not included in our study, however, was the 3-vessel view, which has been found to be a very effective method of assessing the ventricular outflow tracts. In a pilot study, it was found that most screening centers in our region were acquiring the 4-chamber and outflow views as 3 still images, and the acquisition of the 3-vessel view increased the acquisition time substantially compared with the 2 sweeps described above. Our approach is intended to incorporate cine loop sweeps into a routine second-trimester sonographic examination with a minimum of additional acquisition time and sonographer training, and for this reason, we chose not to include the 3-vessel view. The abnormal cases were acquired in a prospective fashion based on availability to the researchers; therefore, they do not rep-
resent a comprehensive sample of congenital heart disease. Relatively speaking, hypoplastic left heart cases are overrepresented, along with atrial ventricular septal defects.

In conclusion, the use of cine loop sweeps is a practical and standardized approach to assessment of the fetal heart during routine obstetric sonographic examinations. This technique poses several advantages compared with review of still images: it has been shown to increase the rate of detection of congenital heart disease while minimizing false-positive identification. The acquisition process is a relatively simple procedure and does not require additional resources other than the capacity to store cine loops within the clinical facility.

Figure 3. Ventricular septal defect associated with tetralogy of Fallot. A. Frame selected from the cine loop sweep, which best shows the defect. B. Still image acquired as a single image by the conventional technique.

The results of this study support the use of standardized procedures, for both acquisition of images and their review and interpretation. By including real-time cine loop sweeps through the fetal heart in a standardized format, the interpreting physician gains access to critically important evidence to guide their decision making. This study shows a trend toward improved prenatal detection of congenital heart disease when standardized cine loops and checklists are included in the prenatal cardiac screening review by expert and nonexpert clinicians. Despite the relatively small sample size, a statistically significant improvement in congenital heart defect detection was shown for 2 of the 7 reviewers. On the basis of this research, further studies with larger sample sizes may support inclusion of cine loop sweeps in routine prenatal screening programs.

References


Increasing Recognition of Fetal Heart Anatomy Using Online Tutorials and Mastery Learning Compared With Classroom Instructional Methods
Ted Edward Scott, Laura Thomas, Keith Edwards, Judy Jones, Hans Swan and Andrew Wessels
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What is This?
Introduction

The majority of deaths from congenital defects in childhood can be attributed to congenital heart disease (CHD).\(^1\) The most common cause of birth defects, CHD is most frequently reported with an incidence of 0.8% of all live births.\(^2\) Numerous studies have shown, however, that the prenatal diagnosis of congenital heart disease can improve clinical outcomes of those affected after birth.\(^3\)–\(^5\) Prenatal diagnosis of congenital heart disease is critically important to ensure optimal management of the pregnancy, optimal delivery of the baby, and provision of support for parental decision making. In addition, those at high risk for CHD may be relieved of additional anxiety and fears caused just by the possibility of CHD by the confirmation of normality.\(^6\)

The role of the sonographer in prenatal diagnosis of congenital heart disease is to assess the fetal heart in real time, including the four chambers and whenever possible the outflow tracts. Typically the sonographer will document normal or abnormal findings as a preliminary report with corresponding still images. The interpreting physician will review the preliminary report and associated images confirming the determination of a normal, abnormal, or an indeterminate finding.

The formal training for diagnostic medical sonographers in the detection of congenital heart defects is provided in didactic form usually within an obstetrics and gynecology sonography course. The clinical training is most often provided within a practicum through clinical
facilities linked to the college program. Imaging and assessing the fetal heart is a challenging task for sonography students. Acquiring images and assessing the fetal heart is a complex task demanding an integrated understanding of the anatomy and physiology of the fetal heart and image recognition skills of rapidly moving structures such as the outflow tracts on the order of 2 to 6 mm in diameter. Unlike abdominal, pelvic, or other sonography exams, students usually do not have any significant opportunity to practice obstetrical sonography in their college imaging laboratories. It is also difficult for education programs to acquire a robust library of sample cases representative of the broad diversity of congenital heart disease.

Addressing complex learning objectives that demand significant skill development from the learner is a challenge for the traditional classroom setting. Skill development demands significant formative assessment and structured feedback, which can be difficult to provide to a group in a classroom environment. For teachers at all levels of education, it remains a challenge to provide customized instruction and high-quality feedback to individuals in large classes.

In a seminal article in 1984, Benjamin Bloom articulated a number of methods to address the two-sigma problem. Bloom found that when using both mastery learning and tutorial-based instruction as compared with conventional classroom instruction, students in the tutorial and mastery learning groups on average increased their achievement levels by two-sigma (two standard deviations). In other words, the average student in the tutorial and mastery group outperformed 98% of the students in the classroom group. Mastery-based instruction proposes that learning should provide formative evaluation with guided or corrective feedback such that students achieve mastery of all of the learning objectives. Tutorial-based instruction assumes that students are working regularly with a good tutor, in a face-to-face mode. Two forms of instruction have emerged to address the opportunity for learning using the theory of the two-sigma problem. These forms include a method of automated feedback based on student performance during practice exercises, and mastery learning, where students work at their own pace to achieve mastery of learning.

In the realm of digitally enhanced education that exists in many postsecondary institutions today, there exists a significant opportunity to provide students with opportunities to leverage the educational theories and applications established by Bloom. Some very popular solutions have emerged from outside the traditional postsecondary sector. Khan Academy is a very popular electronic platform for learning mathematics based on tutorial-based instruction and mastery learning principles. Students are able to traverse the entire spectrum of mathematics necessary to achieve successful preparation for entry into postsecondary institutions. Besides the pedagogical advantages associated with the two-sigma problem, the use of electronic learning tutorials and practice exercises provide numerous advantages compared with traditional classroom learning. These advantages include:

- self-paced progress through the learning objectives,
- opportunity to repeat tutorials anytime anywhere without reliance on a human tutor,
- ability to access experts on niche topics,
- expand the learning opportunity to a global audience in any language,
- ensure a consistent and high-quality learning opportunity,
- provide the tutorial and learning tool designers with valuable quantitative feedback regarding the learning experience that can be used to improve future iterations of the tutorials and tools.

The objective of this study was to determine if a series of online tutorials and practice exercises using a standardized assessment of the fetal heart in real time would be a more effective approach to be used by students when learning how to identify normal fetal heart structures and congenital heart disease. The researchers addressed the following hypothesis

**Hypothesis 1:** Training students to use a standardized assessment technique using tutorials and practice exercises online, compared with traditional classroom instruction, will increase the students’ ability to identify normal fetal heart structures and congenital heart disease.

**Materials and Methods**

This study was approved by the Charles Sturt University Ethics in Human Research Committee, the McMaster University Research Ethics Board (MREB), and the Mohawk College Research Ethics Board prior to initiation. The participants in this study were drawn from the Medical Radiation Science Obstetrical and Gynecologic Ultrasonography 3 class. These sonography students were in the third year of study within a collaborative four-year, Mohawk-McMaster Medical Radiation Sciences program. All 33 students in the class volunteered to participate in this study.

Students were randomly divided into two groups. There were 17 students assigned to the classroom learning (control) group, and 12 of these students completed all of the learning activities. Of the 16 originally assigned to the online learning (experimental) group, 15 students
completed all of the learning activities. The 27 students who completed all of the learning activities formed the basis for final data analysis. Three learning objectives for the experimental and control groups were defined as follows:

1. increased ability to identify normal fetal cardiac structures,
2. increased ability to identify abnormal fetal cardiac structures,
3. increased ability to identify abnormal cases.

Students assigned to the control group were not permitted access to the online tutorials and practice exercises. Students assigned to the experimental group were not permitted to attend the four face-to-face classes and single online tutorial with the course instructor. The online examination was administered within two weeks of the onset of the experiment.

Students enrolled in the control group participated in four classroom lecture periods of 50 minutes each and one online tutorial. The lectures reviewed the anatomy of the fetal heart, the fetal blood flow, and the sonographic views used to image the heart. They also included real-time cineloops with tips and suggestions on how to identify a normal heart. Lectures included review of some of the more common congenital heart abnormalities using real-time cineloops. The tutorial was delivered online with labeled anatomy images, with focused questions pertaining to the diagrams. The time for instruction was approximately 240 minutes, with an allowance for independent study time of 90 minutes, for a total of 330 minutes of time committed to learning.

The experimental group was provided with the “Find It First” tool consisting of 13 brief online tutorials in the use of a five-step method of assessment of the fetal heart prepared by the study investigator, amounting to approximately 75 minutes of instruction in total. Students completed practice exercises online as formative assessment with electronic feedback that required an additional 150 minutes of learning time. The total time committed to learning for the experimental group was approximately 225 minutes.

The students were also provided practice cases for each step of the technique, and these exercises included immediate electronic feedback. Students were required to demonstrate mastery of each step before continuing to the next step of assessment. A screen shot depicting the user interface for the practice exercises provided by module two is provided in Figure 1. Students worked through five online modules representing five steps of analysis considering the anatomic features and relationships as follows:

1. cardiac situs, axis, and size;
2. chamber morphology and function;
3. left ventricular outflow tract (LVOT) continuity with the left ventricle;
4. right ventricular outflow tract (RVOT) continuity with the right ventricle;
5. cross-over of outflow tracts at their origins.

Each of these features and relationships could be defined as normal, abnormal, or not seen. Each module consisted of a brief tutorial to provide examples and instruction on how to assess the relevant anatomic feature. Following the review of each tutorial the students were required to complete 17 sample cases similar to the example depicted in Figure 1. At the end of every series, all of the missed cases were compiled, and the learner reassessed the missed cases until all 17 cases were accurately reviewed. The student could advance to the next module only after successfully demonstrating the ability to analyze the anatomic features covered by the module. As students advanced through the modules, additional steps were added to the analysis until the student reached the fifth module where all five steps and corresponding features were examined, representing a review and analysis of a total of 85 cases.

In order to assess the performance of the students in both groups an online quiz was developed. Each student was provided with a unique and secure user identification and password. Students’ ability to identify normal and abnormal structures was measured by their review of 25 cases of fetal cardiac anatomy. A randomized sequence of 10 abnormal and 15 normal cases were presented. Each case consisted of two cine-loop sweeps through the fetal heart. The situs to four chamber sweep began in the transverse abdominal plane at the level of the stomach and ended at the four chamber view. The four chamber to outflows sweep began in the four chamber view and swept through the ventricular outflow tracts. Students in both groups completed the online examination within two weeks of completing the classroom or online instruction. As described in Figure 2, students were required to identify five anatomic features for each case and determine whether that case was normal, abnormal, or indeterminate. A completely accurate assessment was one that scored each feature accurately and correctly identified the case as normal, abnormal, or indeterminate. The decision framework was standardized for the students using a protocol that defined the following outcomes: a normal result implies no further assessment, an abnormal determination will result in a referral to a pediatric cardiologist, and an indeterminate finding will result in a follow-up reassessment in the obstetric screening center. This evaluation required approximately one hour for the students to complete.
Data Analysis

The chi square test was performed to evaluate the statistical significance of the results of the image analysis. The null hypothesis for this test was defined by the following statement: “After using the computerized learning system (experimental group) or gaining instruction in a traditional face to face classroom environment (control group), there will be no statistical difference in students’ ability to identify normal and abnormal fetal heart
structures.” Differences on the multiple choice evaluations and the confidence levels were tested using the two-tailed t-test for statistical significance.

**Results**

The students were evaluated on their ability to correctly assign one of three conditions, normal, abnormal, or not seen, to five unique anatomic criteria and relationships and correctly define the case as normal, abnormal, or indeterminate. For each case, to be scored as completely correct, all five anatomic criteria and the assignment of normal, abnormal, or indeterminate had to be correct, which required a total of six correct decisions for each case. The students in the control group on average assessed correctly all five anatomic features but determined the normalcy or abnormal status of only 19% of cases, 4.7 of 25 ± 4.4 SD compared with the experimental group mean score of 39% of correctly identified cases, 9.9 of 25 ± 2.7 SD (P < .01). In terms of mean performance difference between the two groups there was a one-sigma (one standard deviation) effect. This can be interpreted to mean that the average score in the experimental group was greater than 84% of the students in the control group. As seen in Figure 3, the experimental group outperformed the control group in every category of assessment.

The abnormal cases depicted in Table 1 represent a typical range of serious congenital heart disease with one or more abnormal anatomical features evident in the
cine-loops provided to the students for review. As shown in the table, the experimental group outperformed the control group in 7 of 10 abnormal cases ($P < .01$). Specifically in five abnormal cases, D-TGA, single ventricles, large heart, HLHS, and truncus arteriosus, a greater than two-thirds majority of experimental students identified these cases whereas the control group only identified 1 case, truncus arteriosus by a two-thirds majority of students ($P < .01$). The experimental group performed particularly poorly in detecting Ebstein’s anomaly, displacement of the septal leaflet of the tricuspid valve typically causing regurgitation, with only a 7% detection rate compared with 33% for the control group.

**Discussion**

The strategy adopted by most sonography programs for teaching students to identify the presence of pathology during abdominal or pelvic examinations is typically based on providing students with a significant amount of supervised practice and exposure to the normal sonographic appearances of anatomic structures. In teaching students to identify the presence of pathology, sonography programs begin with a focus on the normal anatomic appearance of the structure. In this way, students develop expectations in terms of the visualization of relationships and structures that establish normalcy. Once understanding of normalcy is firmly grasped and rooted in the student’s experience, most programs and courses attempt to provide a framework for pathology such that students can focus their attention on links between the patient’s history and the probable associated pathology. For example, a history of right upper quadrant pain and elevated liver enzymes would draw the sonographer’s attention to the liver and biliary tree. To put this educational paradigm in simpler terms, if the signal is the presence of pathology and the factors contributing to missing the detection of pathology are defined as noise, a sonographer can think about enhancing the signal to noise ratio in order to identify pathology more frequently. To simplify this analogy, if the pathology is the *signal*, and the factors that influence missed detection of a pathology are the *noise*, then the sonographer’s task is to enhance the signal to noise ratio in an effort to increase the detection rate of pathology. A deeper understanding of frequent sonographic appearances of pathology relative to patient history will strengthen the signal. The sonographer’s ability to optimize image quality, perform a complete real-time interrogation, and apply systematic examination techniques will help to reduce the noise. In this way, the presence of pathology (signal) can be enhanced during the sonographic examination.

Part of the challenge for detecting congenital heart disease in utero is the fact that most often it is found in the low-risk population. This makes it more difficult to detect because one cannot usually rely on clues from the patient history (signal) to focus the examination. Furthermore, as a screening examination, the inherent bias is an expectation of normalcy. In this setting the ability to reduce noise to enhance what is a weak signal becomes a very important consideration. Standardizing imaging procedures and assessment protocols represents an important consideration in this regard and one that was adopted for this learning tool.

In addition to the two-sigma pedagogy, the online learning tutorials and practice exercises focused nearly exclusively on exposing students in the experimental group to as many normal and abnormal cases as possible in a step-wise learning methodology. The focus for the learner was on practicing the decision making for each step in each module until mastery of the concept was achieved.

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**Table 1. Detection rate by group according to the individual cases of congenital heart disease.**

<table>
<thead>
<tr>
<th>Case</th>
<th>Experimental Group, n = 15</th>
<th>Control Group, n = 12</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Large heart</td>
<td>13 (93)</td>
<td>7 (58)</td>
<td>35</td>
</tr>
<tr>
<td>2 Truncus arteriosus</td>
<td>12 (80)</td>
<td>9 (75)</td>
<td>5</td>
</tr>
<tr>
<td>3 Hypoplastic left heart</td>
<td>12 (80)</td>
<td>6 (50)</td>
<td>30</td>
</tr>
<tr>
<td>4 D-TGA</td>
<td>11 (73)</td>
<td>7 (58)</td>
<td>15</td>
</tr>
<tr>
<td>5 Single ventricle</td>
<td>10 (67)</td>
<td>6 (50)</td>
<td>17</td>
</tr>
<tr>
<td>6 AVSD</td>
<td>7 (47)</td>
<td>5 (42)</td>
<td>5</td>
</tr>
<tr>
<td>7 Tetralogy of fallot</td>
<td>7 (47)</td>
<td>2 (17)</td>
<td>30</td>
</tr>
<tr>
<td>8 Hypoplastic left heart</td>
<td>7 (47)</td>
<td>7 (58)</td>
<td>–11</td>
</tr>
<tr>
<td>9 Tetralogy of fallot</td>
<td>3 (20)</td>
<td>4 (33)</td>
<td>–13</td>
</tr>
<tr>
<td>10 Ebstein’s anomaly</td>
<td>1 (7)</td>
<td>4 (33)</td>
<td>–26</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>83 (55)</td>
<td>57 (48)</td>
<td></td>
</tr>
</tbody>
</table>
achieved. In the classroom learning group, a broader focus was taken and students were given more contextual information related to the normal and abnormal heart. There was less emphasis on skill development with feedback in the classroom setting.

Bloom’s two-sigma theory was not replicated in this study; however, a one-sigma improvement was found and this represents a twofold increase in the percentage of cases accurately classified by students in the experimental group, 39% compared with 19% in the control group. Further, the experimental group did not benefit from any face-to-face learning opportunities. This might also explain why a two-sigma effect was not achieved. The ability to correctly classify anatomic features and relationships was consistently demonstrated across all five categories. This suggests that students acquired improved image interpretation skills in the experimental group as compared to the control group.

The majority of congenital heart defects (7/10) were identified with greater frequency by the experimental group compared with the control group. In addition, the experimental group was much more consistent as a group in identifying 5 of 10 defects with a greater than two-thirds majority of the group compared with the control group, which only achieved a two-thirds majority correct identification for one abnormal case. These results suggest that the use of mastery-based instruction in the form of practice exercises framed in a step-wise protocol might lead to a more consistent development of image interpretation skills. The particularly poor performance of the experimental group with respect to the Ebstein’s anomaly may be due to the fact that it was not included as an example during the online tutorials and it represents the singular isolated abnormality of an apical displacement of the tricuspid valve. The online tutorials emphasized more frequently encountered structural abnormalities, including presence of ventricular septal defects, discontinuity of the outflow tracts, disparity in chamber size, heart size and angulation, among other factors. Future versions of this learning tool can be expanded to correct this oversight.

This study was limited in a number of ways. The number of participants was relatively small and representative of a single cohort of sonography students. Five of the 17 students in the control group did not complete the study while only one of the students in the experimental group did not complete the study. The students in the experimental group may have persisted through the final evaluation and completed the study in a greater percentage due to their familiarity with the “Find It First” learning tool. Some of the students from the classroom (control) group may have found the final evaluation provided on the “Find It First” tool to be unfamiliar and this may have been enough to deter them from completing the study. The online learning tutorials and practice exercises were first generation and improvements in content and technical terms can be achieved in future generations of this application. Finally, the performance of the students in the control (classroom) group was dependent on a single instructor and this could bias the outcome of the student’s learning in either a positive or negative direction.

Conclusion

In this study it was shown that students’ ability to correctly classify normal and abnormal fetal cardiac anatomy can be improved using principles of mastery learning and tutorial-based instruction in an online format. Further, the opportunity to exploit the benefits of online learning may provide students with greater access to high-quality learning opportunities. Students may benefit from a self-paced approach to learning with the opportunity to review tutorial sessions anytime, anywhere as much as desired.

Assessment of the fetal heart for congenital heart disease is a challenging task and one that demands significant educational expertise in the domains of cardiovascular and obstetrical practice areas. For topics that demand complex analysis and clinical expertise at the intersection of clinical skills such as fetal cardiac assessment, an online tutorial-based approach may prove to be a very effective means of addressing this teaching and learning challenge.

In this study, students using the online tutorial and practice exercises had improved performance by one standard deviation compared with students using traditional classroom-based learning methods. Further examination of this approach, including quantitative analysis of the user experience, may identify opportunities to refine and improve this approach to learning how to assess the fetal heart. Future studies may demonstrate benefits to other stakeholders including practicing clinical sonographers and interpreting physicians. It may prove worthwhile for other educational applications to be developed using this methodology as well, particularly those areas of sonographic practice that are not fully addressed through traditional curriculum. Examples where online tutorial-based instruction might be developed include musculoskeletal imaging, volume imaging, and imaging of the bowel.

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