Optimal kVp in chest computed radiography using visual grading scores: a comparison between visual grading characteristics and ordinal regression analysis

Xiaoming Zheng*, Myeongsoo Kim*, Sook Yangb
a Medical Radiation Science, School of Dentistry and Health Sciences, Faculty of Science, Charles Sturt University, Wagga Wagga, NSW 2678, Australia; b Biomedical Engineering, Faculty of Engineering, Chonnam National University, Gwangju, South Korea.

ABSTRACT

The purposes of this work were to determine the optimal peak voltage for chest computed radiography (CR) using visual grading scores and to compare visual grading characteristics (VGC) and ordinal regression in visual grading analysis. An Afga CR system was used to acquire images of an anthropomorphic chest phantom. Both entrance surface dose and detector surface dose were measured using the Piranha 657 dosimeter. The images were acquired under various voltages from 80 to 120 kVp and exposures from 0.5 to 12.5 mAs. The image qualities were evaluated by 5 experienced radiologists/radiographers based on modified European imaging criteria using 1-5 visual grading scale. The VGC, ordinal regression as well as the conventional visual grading analysis (VGA) were employed for the image quality analysis. Both VGC and ordinal regression yielded the same results with both 100 kVp and 120 kVp producing the best image quality. The image quality of the 120 kVp was slightly higher than that of the 100 kVp but its dose was also higher than that of the 100kVp. On balancing image quality with dose, the 100 kVp should be the optimal kVp for the chest imaging using the Afga CR system. The ordinal regression is a powerful tool in the analysis of image quality using visual grading scores and the VGC can be handled by the ordinal regression.

Keywords: Computed radiography; Chest imaging; Optimal peak voltage; Visual grading analysis; Visual grading characteristics; Ordinal regression; Image quality; Radiation dose.

1. INTRODUCTION

Peak voltage kVp is one of the important scan parameters in the optimization of computed radiography (CR). Determining an optimal kVp for chest CR imaging is not a trivial task owing to its anatomical complexity and diverse clinical indications which may require opposing kVps. Image quality is the key for the optimization of CR imaging but it is not well defined for it is clinical task dependent and involves human observers. Various image quality indexes have been used in the CR system optimization including objective parameters, such as contrast to noise ratio, and subjective parameters, such as the contrast-details studies. Perhaps the best image quality index should be the area under the receiver operating characteristics (ROC) curve, AUC, in the ROC studies. However, the ROC studies are generally tedious and often restrictive. Visual grading scores (VGS) of image quality is more popular clinically but its data needs to be analyzed carefully because the VGS value is ordinal in nature. In the conventional visual grading analysis (VGA), the visual grading scores are averaged depending on the questions in hand. For example, the visual grading score for a set of images under various exposures with a fixed peak voltage and evaluated by a number of observers on a number of image quality criteria would be an average of all these individual scores. These results are useful provided that the underline variables are random. In order to overcome the ordinal nature of the VGS, visual grading characteristics (VGC) and ordinal regression methodologies have been successfully applied in the visual grading analysis of the image quality. The VGC methodology was inspired by the ROC studies and is mainly used in comparison between two imaging system’s parameters. Ordinal regression, on the other hand, is a more general approach that can be employed to handle multiple factors simultaneously.
Radiation dose to patient is another important parameter in the optimization of the scan parameters in CR imaging, although the dose to patient in chest X-ray imaging is relatively small\textsuperscript{1,2,3,4,11}. The European guidelines recommend that the kVp for chest imaging should be within the range of 100-150 kVp\textsuperscript{12}. Recent studies\textsuperscript{8,15} have demonstrated that a better image quality can be achieved at a lower kVp for a constant effective dose to patients. Despite these results, the higher kVp is still recommended in clinical practice\textsuperscript{14} as a lower dose to patients can be achieved by reducing the exposure (mAs), following the rule of “15% kVp increase half the mAs”, without compromise the image quality\textsuperscript{15,16}. The purposes of this work were to determine the optimal kVp for chest imaging using clinically popular visual grading scores of imaging quality and to compare visual grading analysis methodologies of visual grading characteristics (VGC) and ordinal regression in the assessment of image quality.

2. METHODS

An Afga compact plus CR system with a C\textsubscript{4}I photodiode/TFT detector was used to acquire images of an anthropomorphic chest phantom. The images were acquired under various voltages from 80 to 120 kVp and exposures from 0.5 to 12.5 mAs. Both entrance surface dose and the detector surface dose were measured using the Piranha 657 dosimeter of RTI Electronics AB of Sweden. The image qualities were evaluated by 5 experienced radiologists/radiographers based on modified European image criteria\textsuperscript{12} using 1-5 visual grading scale: 1, unacceptable; 2, below acceptable; 3, just acceptable; 4, above acceptable and 5, most acceptable. The observers were asked to grade the images using the 1-5 scale on each of the following five quality criteria: media sternum, parenchyma, bronchus, noise, contrast and abnormality. The visual grading scores (VGS) were then grouped according to the applied kVp and analyzed by the following three methods: 1, conventional visual grading analysis (VGA)\textsuperscript{8}; 2, visual grading characteristics (VGC)\textsuperscript{9}; and 3, ordinal regression (OR)\textsuperscript{10}. For conventional VGA, the visual grading score for each of the images were calculated as:

\[ \text{V GAS} = \frac{\sum_{c=1}^{C} \sum_{o=1}^{O} G_{c,o}}{S \times O} \]  

(1)

Where: \( G_{c,o} \) is the grading score of an image on each of the image criteria by each of the observers. \( C \) is the number of criteria and \( O \) is the number of the observers. These VGAS were then plotted against their detector surface dose under various kVps.

For the VGC analysis, the images’ raw visual grading scores were grouped according to their kVp and the kVps were paired as 80:90; 90:100; 100:110, 110:120 for their individual pair comparison. An online program of JROCFIT from John Hopkins University\textsuperscript{17} was used to calculate the area under the VGC curve, AUC\textsubscript{VGC}. Four separate calculations were carried out for each of the four kVp pairs and their combined values of the AUC\textsubscript{VGC} were then plotted against the kVp taking the 80kVp as the reference. For the ordinal regression analysis, the SPSS statistical software package (version 20) was employed and the image’s raw visual grading scores were set as dependent and the kVps as the factors. Both individual comparisons between two kVp’s image groups and a comparison among all kVp’s (taking all images as a whole set) were analyzed using the SPSS. The outputs of the parameter estimates were then plotted against the kVp taking the 120 kVp as the reference.

3. RESULTS

Figure 1 shows the measured entrance surface dose against the measured detector surface dose. It shows that the detector surface dose is linearly proportional to the entrance surface dose. The dose difference (absorbed dose) is also proportional to the entrance surface dose and the exposure index lgM is proportional to the detector surface dose (not shown). Figure 2 shows the entrance surface dose vs the kVp applied under a constant exposure (mAs=5). The entrance surface dose is linearly proportional to the kVp applied under a constant exposure. These results are consistent with recent works of Tavares et al\textsuperscript{18} and Zaïnon et al\textsuperscript{19}. Figure 3 shows the results of the conventional visual grading analysis where the VGAS were plotted against the detector surface dose. The image quality is generally increased as the dose is...
increased. However, under a fixed kVp, the image quality is dropped beyond some dose points (around 0.3-0.4 mGy) and then increased again as the dose is increased. Ma et al. also reported that the image quality was increased as the dose was increased but dropped beyond some dose points. The overall combined image quality (all kVps combined) can be fitted into a linear function ($r^2=0.52$) which is consistent with a recent results of Tavares et al. The doses at the just acceptable image quality (VGAS=3) were extrapolated from the curves as 0.249, 0.120, 0.146, 0.160 and 0.162 mGy for 80, 90, 100, 110 and 120 kVp, respectively. The doses at the just acceptable for diagnosis image quality level are generally increased as the kVp is increased except for the 80 kVp. Ma et al. also reported that the minimum effective dose for acceptable image quality was increased as the kVp was increased.

![Graph 1](image1.png)

**Figure 1:** The measured entrance surface dose (mGy) vs the measured detector surface dose (mGy).

![Graph 2](image2.png)

**Figure 2:** The measured entrance surface dose (mGy) vs the applied kVp under a constant exposure (mAs=5).
The visual grading characteristics (VGC) calculations were carried out by comparing two kVps at a time, i.e. compare 80-90, 90-100, 100-110 and 110-120 kVp pairs, individually. These areas under the curve, \( \text{AUC}_{ \text{VGC} } \) were calculated to be 0.5046, 0.5915, 0.4687 and 0.5351 for the above kVp pairs, respectively. The \( \text{AUC}_{ \text{VGC} } = 0.5 \) means equal image quality whilst \( \text{AUC}_{ \text{VGC} } > 0.5 \) means that the vertical kVp is better than the horizontal kVp in the VGC plots. Figure 4 shows the VGC plots for the comparison of the 80-90 kVp pair where 90 kVp is on the vertical axis. The \( \text{AUC}_{ \text{VGC} } = 0.5046 \) suggests that the image quality of the 90 kVp is slightly better than that of the 80 kVp. Figure 5 shows the combined comparison among all kVps. It shows two maximum image qualities at 100 and 120 kVps. The 100 kVp is better than both 90 and 110 kVps and the 110 kVp is lower than both 100 and 120 kVps. The 120 kVp is the highest in terms of image quality.

Figure 3: The image quality VGAS vs detector surface dose (mGy) under various kVp.

Figure 4: The VGC plots for the image quality comparison between 80 kVp and 90 kVp. The \( \text{AUC}_{ \text{VGC} } = 0.5046 \) suggests that the image quality of 90 kVp is slightly better than that of the 80 kVp.
Figure 5: The combined plot of comparisons among all kVps from the VGC calculations. The image qualities of the 100 and 120 kVp are better than that of the rest kVps.

Using the SPSS package, the ordinal regression analysis has been carried out both in comparison of two kVps at a time, similar to the VGC analysis, and in taking all images as a whole data set and comparing the various kVps simultaneously, where the VGS was the dependent variable and various kVps were the factors. For individual kVp pair comparisons, the location values were calculated to be -0.291, -0.820, 0.199 and -0.251 for 80-90, 90-100, 100-110, and 110-120 kVp pairs, respectively, taking the higher kVp as the reference zero. For the analysis of all images as a whole data set, the location values were determined to be -0.583, -0.558, -0.037, -0.242 for 80, 90, 100, 110 kVps, respectively, taking the 120 kVp as the reference zero, as shown in table 1.

Table 1: Parameter estimates from the ordinal regression using SPSS by taking all images as a whole. The link function is logit.

<table>
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<th>Threshold</th>
<th>Estimate</th>
<th>Std. Error</th>
<th>Wald</th>
<th>df</th>
<th>Sig.</th>
<th>95% Confidence Interval</th>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>Location</td>
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<td>491.055</td>
<td>1</td>
<td>.000</td>
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<td>.000</td>
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<tr>
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<td>.239</td>
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<tr>
<td>[VAR00009 = 4.00]</td>
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<td>95.299</td>
<td>1</td>
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<tr>
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<td>.139</td>
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<td>1</td>
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<td>-8.55</td>
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<tr>
<td>[VAR00010=90.00]</td>
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<td>15.936</td>
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<tr>
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<td>.138</td>
<td>0</td>
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a. This parameter is set to zero because it is redundant.
These results show that the 120 kVp has the highest image quality whilst the 100 kVp comes in second and is very close to the 120 kVp in terms of image quality. These results are the same as the results from the VGC analysis as shown in figure 5. Our results show that there are multiple best kVps for the chest CR imaging as shown in figure 5. Our results show that there are multiple best kVps for the chest CR imaging in terms of image quality. The ordinal regression is a powerful and flexible tool in the visual grading image quality analysis as it can handle individual kVp comparisons as well as analyze various kVps as a whole set which is in contrast to that of the VGC analysis.

4. DISCUSSIONS

The goal of medical X-ray imaging is to acquire the best image quality for diagnosis with a minimum radiation dose to patients. The key to this optimization is the relationship between the image quality and radiation dose\textsuperscript{20}. The image quality is generally increased as the dose is increased. Figure 3 demonstrated a weak linear relationship ($r^2=0.52$) between the dose and image quality in chest X-ray imaging, consistent with a recent work of Tavares et al\textsuperscript{16}. Other works appeared to have a logarithmic relationship\textsuperscript{21,22}. A dose efficient index may be defined as the slope of the linear function between the image quality and the dose, which is the ratio of the image quality to radiation dose. This is in fact termed as the figure of merit (FOM) and is often used in the optimization of scan parameters\textsuperscript{23}. Under a fixed kVp, however, the relationship between the image quality and dose, shown in figure 3, is not strictly linear. It is not possible in this case to use the slope of the linear function, or, the figure of merit, to determine the best kVps. These results are quite different from those of CT phantom studies\textsuperscript{24,25}.

Both visual grading characteristics and ordinal regression results shown in figures 5 and 6 are the same and multiple kVps were found to have the maximum image quality in the chest imaging using the Afga compact plus CR system. The 120kVp is slightly better than the 100kVp in terms of image quality, however, its dose at the just acceptable image quality level (VGAS=3) is also higher (0.163mGy) than that of the 100kVp (0.146mGy). In order to determine the optimal kVp for the chest CR imaging, we need to balance image quality with dose and the 100 kVp should be the optimal kVp for the chest CR imaging. It suggests that a combination of the VGA, VGC or ordinal regression may be required for the scan parameters optimization. In this work, the VGC or ordinal regression was used to analyze the image quality and the conventional VGA was employed to study the dose.

In comparing the VGC and the ordinal regression, we have seen that multiple steps were required in VGC in order to compare the image quality under various kVps (more than two). Methodologically, the VGC is looking at the occurrence frequencies of each of the VGS scores and comparing distributions of the two using maximum likelihood fit of a
binormal mode. In contrast, the ordinal regression within the SPSS package is also looking at the VGS occurrence frequency distributions employing a more general linear regression based on an ordinal logistic model. It can handle multiple distributions simultaneously. Therefore, the VGC analysis can be handled easily by the SPSS’s ordinal regression.

5. CONCLUSIONS

Multiple peak voltages of 100 and 120 kVps were found to have the best image quality for chest imaging using the Agfa compact plus CR system. The 120 kVp has a slightly higher image quality than that of the 100kVp but the radiation dose is also higher than that of the 100kVp at the just acceptable image quality level. On balancing the image quality with radiation dose, the 100kVp should be the optimal kVp for the chest imaging. The ordinal regression within the SPSS package is a powerful tool for the visual grading analysis of the image quality and the visual grading characteristics can be considered as a special case of the ordinal regression. The conventional visual grading analysis (VGA) is useful in the studies of the relationship between image quality and radiation dose and for the determination of the radiation dose at the acceptable image quality level.

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REFERENCES