The Effect of JPEG Compression on Automated Detection of Microaneurysms in Retinal Images

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ABSTRACT

As JPEG compression at source is ubiquitous in retinal imaging, and the block artefacts introduced are known to be of similar size to microaneurysms (an important indicator of diabetic retinopathy) it is prudent to evaluate the effect of JPEG compression on automated detection of retinal pathology. Retinal images were acquired at high quality and then compressed to various lower qualities. An automated microaneurysm detector was run on the retinal images of various qualities of JPEG compression and the ability to predict the presence of diabetic retinopathy based on the detected presence of microaneurysms was evaluated with receiver operating characteristic (ROC) methodology. The negative effect of JPEG compression on automated detection was observed even at levels of compression sometimes used in retinal eye-screening programmes and these may have important clinical implications for deciding on acceptable levels of compression for a fully automated eye-screening programme.

Keywords: retinal imaging, microaneurysms, automated eye screening, JPEG compression

1. INTRODUCTION

There is now, for a variety of reasons, much interest in developing automated computer algorithms for detecting and quantifying features and lesions that occur in retinal images, that is, images of the human retina. The idea is that a retinal image can be captured digitally at source and a computer can be used to analyse the image and report on the presence of disease or the progression of disease since the last visit of the patient. A simpler task of particular interest is to recognise the presence or absence of some specific disease suitable for retinal eye-screening programmes. By automating this task the screening programme can potentially be made cheaper, more efficient, and easier to operate in remote centres. There is also the potential to free up ophthalmologists, who are in short supply worldwide, for other work.

Consumer Digital SLR camera technology, as the back-end camera to a fundus camera, is now commonly used in eye clinics and in retinal eye screening programmes. As these cameras typically provide images in JPEG (Joint Photographic Experts Group) format, and data storage for archiving the very large numbers of images from screening programmes can be limited, use of JPEG compression is ubiquitous in retinal imaging. JPEG compression is a lossy compression. Not only is it impossible to recover the original image data as provided by the camera sensor there is a loss of general image quality with artefacts introduced into the image. It is almost unavoidable, due to user client software constraints, to be working with images of the retina degraded by JPEG compression in routine eye clinic work and eye screening programmes. A number of studies on the ability of ophthalmologists to detect and grade the presence of clinically significant disease in JPEG degraded retinal images have supported the not uncommon assumption that a certain amount of JPEG compression can safely be tolerated in retinal images.

The problem for automated detection of retinal pathology when using images compressed with JPEG compression is that certain features of interest (such as small lesions) occur on the same scale as artefacts introduced by the compression. Some proposed automated detection algorithms rely on detecting small lesions and it is likely that JPEG compression has an adverse effect that may be clinically intolerable. The effect of JPEG compression on automated detection of retinal pathology, to our knowledge, has hardly been studied. In this paper we explore the effect of JPEG compression on predicting the presence of diabetic retinopathy (disease of the retina

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due to diabetes) using the automated detection of microaneurysms (a small lesion that indicates the presence of diabetic retinopathy) as the predictor of retinopathy. The study involves the JPEG compression of high quality images to lower quality and running an automated microaneurysm detector on the JPEG compressed images. Receiver operating characteristic (ROC) graphs are plotted for the ability to predict diabetic retinopathy for various qualities (equivalently compression ratios) of images.

In the following sections we first explain why microaneurysms are a useful target for detecting diabetic retinopathy and give an overview of the implementation history of automated microaneurysms detectors. Then JPEG compression is described with attention to the lossy component of the compression, the artefacts introduced and how they might be troublesome for automated detection of microaneurysms. Following that we describe and present results of the study to test for the ability to detect diabetic retinopathy using an automated microaneurysm detector on JPEG compressed images.

2. BACKGROUND

2.1. Automated Microaneurysm Detection

Diabetic retinopathy is a microvascular disease of the retina due to diabetes and is the leading cause of blindness in the Western working age population. It is a growing health problem of some concern. With early detection of the disease, treatment of diabetic retinopathy is effective at reducing eye-sight loss. Programmes to screen known diabetic persons for diabetic retinopathy currently involve manual reading of retinal images by ophthalmologists, who are in short supply worldwide. Computer automation of diabetic eye-screening programmes using digital imaging and pattern recognition techniques would provide the potential to reduce costs, give timely responses to patients and enable programmes to be run in rural areas where ophthalmologists and high internet bandwidth are not available.

Computer analysis of retinal images for the detection and grading of diabetic retinopathy is being pursued by quite a number of research groups as images of the retina provide a very rich field for pattern recognition research. There are a number of lesions of the retina that indicate retinopathy, with the most important for detecting the early stages of the disease being microaneurysms, exudates and haemorrhages. The number of microaneurysms has been shown to correlate with the severity and likely progression of the disease, at least for its early stages. They are often the first lesion clinically visible and are unlikely not to be visible in a retina more severely affected by diabetic retinopathy. Microaneurysms appear as small round red dots separated from the vasculature, as the capillaries from which they grow are not visible at achievable image resolution. We are exploring the automated detection of microaneurysms as a means of screening for diabetic retinopathy.

Early attempts to detect microaneurysms worked on fluorescein angiographic images, a process in which fluorescein injected into the blood stream highlights the vasculature, including microaneurysms, in images. The first useable and somewhat verified microaneurysm detector was described by Cree et al. The use of fluorescein angiography is unsuitable for the screening of diabetic retinopathy because of associated health risks, so Hipwell et al. modified the microaneurysm detector of Cree et al. to work on red-free images and evaluated its use in an eye-screening situation and concluded that it could safely identify 50% of healthy retinae, thus almost halves the workload of the ophthalmologists as the proportion of subjects with diabetic retinopathy is a small fraction of the total screened population. Red-free images are images captured with a blue-green filter inserted in the optical path of the camera, and were advantageous at the time of the work of Hipwell and coworkers as only monochromatic digital cameras had the sensitivity and resolution necessary for retinal imaging. As high resolution colour digital cameras are now readily available we are exploring analysing colour images for the presence of microaneurysms.

2.2. JPEG compression

The introduction of high resolution colour SLR digital camera technology to digital retinal imaging has also brought lossy image compression in the form of JPEG (Joint Photographic Experts Group) compression. The JPEG standard is available as ISO/IEC IS 10918-1. It is worth noting that the JPEG standard does provide for lossless compression however this facility is rarely implemented in software using JPEG compression.
compression leads to three primary artefacts: smoothing of image data, ringing about sharp edges and block effects on a $8 \times 8$ pixel basis. The ability to be able to grade and make clinical judgements from JPEG compressed retinal images has been examined in a number of studies, however these studies have almost all focussed on the ability of specialists to read the images, with quite a few using image or display resolution that is now known to be insufficient for recognising small lesions such as microaneurysms or the fine detail of neovascularisation (new vessel growth). A summary of those studies is that those using questionable resolution (about $800 \times 600$ pixels) find that specialists overly misgrade retinal images with compression ratios as low as 30:1\textsuperscript{11–13}, whereas those that use a more suitable higher original image resolution find that higher compression ratios can be sustained\textsuperscript{14,15}. For example, Baker et al.\textsuperscript{16}, who used image resolution of $3040 \times 2008$ pixels\textsuperscript{1} (6 megapixel effective resolution) find no problems with image compression ratios as small as 113:1. As to what constitutes a suitable resolution for retinal imaging, a theoretical calculation of needed resolution to resolve the smallest microaneurysms leads to a minimum requirement of $1360 \times 1000$ pixels\textsuperscript{17}.

With the advent of automated analysis of retinal images, and of pattern recognition techniques focussed on detection of very small lesions such as microaneurysms, it is an interesting, and somewhat open, question as to how such techniques will perform on images compressed with the lossy JPEG standard. We are only aware of two studies that examined the effects of JPEG compression on automated retinal image analysis. As part of a larger study of assessing specialists’ ability to read JPEG retinal images, Lee et al.\textsuperscript{15} also assessed a semi-automated procedure for detecting and measuring the area of drusen in retinal images. They found no significant difference in drusen area measurements for JPEG compression of 30:1 against original image data, and did not attempt a comparison for 80:1 image compression as the image quality was obviously visually degraded. Of more importance to the current work is H¨ansgen et al.\textsuperscript{18} in which automated microaneurysm detection on JPEG and wavelet compressed fluorescein angiographic images was tested with the microaneurysm detector of Cree et al.\textsuperscript{9} Using a test-bed of 20 retinal images of $35^\circ$ field-of-view (FOV) at $1024 \times 1024$ resolution, they found that a loss of sensitivity and an increasing false-positive detection rate of microaneurysms was noticeable at a JPEG compression ratio of 10:1 and started to become severe at about 20:1 compression ratio. The wavelet compression proved to be less disastrous for microaneurysm detection.

That wavelet compression is a better compression method than the discrete cosine transform (DCT) used in standard JPEG compression has been recognised by JPEG. The newer 2000 standard has replaced the DCT with a wavelet compression method and provides better image quality for the same compression ratio. Unfortunately this standard is not yet supported by currently available commercial fundus cameras and retinal imaging suites.

It is typical, as in all the above reported studies, to give JPEG compression ratios (resultant JPEG image size divided by raw image data size) as a measure of how much the images are compressed. The larger compression, that is, smaller resultant image size, generally the lower the quality of the image and the more noticeable the introduced artefacts. Nevertheless compression ratios do not fully characterise the resultant image quality and may not be directly comparable between studies. This comes about for two reasons: (1) JPEG compression involves a number of steps and quite a few parameters that are not directly accessible to the user. The mapping of the typically provided quality factor to the parameters (and particularly the quantisation tables used for JPEG compression) is software package dependent. Thus the quality factor of one package does not produce the same compression as that of another package with the same quality factor. (2) As the final step in JPEG compression Huffman compression, a lossless entropy coding compression, is applied to the JPEG bit stream. The amount of compression achieved is dependent on the nature of the original image. This has implications for retinal imaging because retinal images from the fundus camera have a circular aperture whereas the SLR camera sensor normally is rectangular with a 3:2 aspect ratio. Thus digital retinal images often contain substantial black areas on each side of the image. The Huffman compression of the JPEG process compresses black areas very effectively, thus a retinal image with substantial black area is compressed with a larger compression ratio than a retinal image that has been digital captured much more closely cropped to the fundus camera aperture.

In this study we report both the quality setting and resultant compression ratios. All JPEG compression is performed by software that uses the Independent JPEG Group’s open source JPEG compression library libjpeg

\textsuperscript{†}Baker et al. reported resolution as $2008 \times 3040$ pixels, however it is likely they have reported rows by columns rather than the more commonly reported width by height.
3. THE WAIKATO AUTOMATED MICROANEURYSM DETECTOR

The Waikato automated microaneurysm detector is used as the automated detector for testing in this study. It is based around the algorithm due to Spencer et al.\(^7\) and refined by Cree et al.\(^8,9\) into the first system described that successfully and reliably detected microaneurysms in fluorescein angiographic retinal images. Spencer et al.\(^7\) established a procedure of: shade-correction of the images to remove low-frequency shading; a top-hat morphological filter with long linear structures at various orientations to remove blood vessels; matched-filtering with a circular symmetric Gaussian model and thresholding to highlight candidate objects for microaneurysms; region-growing to carefully delineate the candidates’ morphology followed by feature measurement and classification to identify microaneurysms. Cree et al.\(^9\) implemented better region growing and classification algorithms and achieved 82% sensitivity with 5.7 false-positive detections per image for detecting and correctly locating microaneurysms in angiographic images. This sensitivity is only 8% less sensitivity at the same false-positive rate than that achieved by ophthalmologists trained in microaneurysms counting and retinal image grading. This automated microaneurysm detector was used in a study of microaneurysm growth and regression over time\(^{19}\).

Fluorescein angiography studies involve an unacceptable health risk for screening, hence a new automated microaneurysm detector – the Waikato microaneurysm detector – was developed for detecting microaneurysms in colour retinal images. The processing to identify the locations of candidate microaneurysms is similar to that described by Spencer et al.\(^7\), however morphological reconstruction\(^{20}\) has been incorporated to improve the removal of blood vessels and an extra pre-filtering of the image with a median filter before region-growing reduces the risk of the region growing spilling. All processing up to and including the region growing is performed on the green plane of the retinal image as microaneurysms are well distinguished in the green plane.

Whereas the preprocessing stages use only the green information to find candidate microaneurysms, the full colour information is available to the final classifier. A straightforward colour normalisation process is applied to the colour images to reduce intra- and inter-patient variability in retinal image appearance\(^{21}\). This is necessary as the populations under study include peoples of varying ethnicities (Caucasian, Asian and Polynesian are all represented) and the appearance of retinal images varies considerably depending on the amount of melanin present in the retinal pigment epithelium of the subject. A total of seven features measured on the candidate microaneurysms, including information from each of the red, green and blue fields of the colour normalised images, are sufficient to distinguish microaneurysms from other confounding objects. Interestingly it was found that inclusion of information from the blue colour plane did give a small but useful improvement in classification power. This goes against conventional wisdom that the amount of information in the blue part of the spectrum of retinal images is negligible. We suspect that our population of images, which contain a higher proportion of Polynesian subjects than studies carried out on European or North American subjects, hence images containing much more blue component than as typical, might explain this observation.

The Waikato microaneurysm detector used in this study uses a Naïve Bayes classifier to distinguish microaneurysms from other spurious objects thrown up from the preprocessing stage. The Naïve Bayes performed significantly better than linear discriminant analysis. Indeed some other classifiers were found to better Naïve Bayes classification for this particular problem set, however the very slight gains obtained did not outweigh the substantial increase in processing time.\(^5\)

4. EXPERIMENTAL METHODOLOGY

Two sets of retinal images: the ‘training images’ and the ‘testing images’ were used for testing the effects of JPEG compression on automated microaneurysm detection. We first describe the training image dataset.

Eighty digital colour retinal images were acquired with a Topcon mydriatic fundus camera and Nikon D1X SLR camera at 5.5 megapixel effective resolution of a 50° field-of-view of the retina, from 68 individuals with diabetes. Even though there are pairs of images of the same individual, the images are always of non-overlapping
fields or of different eyes of the individual. Of the 80 images, 20 were graded as not having any retinopathy and
60 were graded as having retinopathy by a consultant ophthalmologist.

The images were captured at ‘high quality’ JPEG resolution and then cropped to the fundus camera aperture
(about 2100 × 1800 pixels). Examination of the image file header data reveals that the JPEG images were
converted to YUV colour space with the two chroma channels (U and V) subsampled to half resolution in both
the vertical and horizontal directions (as is typically done in JPEG compression) and the quantisation tables
were identical to that produced by the software of the Independent JPEG Group when set to 95% quality. These
80 images are the same images that were used to design the Waikato automated microaneurysm detector, and to
train the Naïve Bayes classifier stage, hence we refer to these images as the ‘training images’. Ethical permission
to use the training images for this study was obtained from the Waikato Ethics Committee.

The use of high quality JPEG compressed images as baseline images in the training data set instead of original
image data could be criticised, however we note that image degradation has already occurred as part of the image
capture process because of the use of pixel resampling within the Nikon camera (from the 4024 × 1324 pixel grid
of the imaging sensor to the 3008 × 1960 pixel grid output by the camera) and use of colour interpolation from
the Bayer mask pattern used in the CCD sensor to achieve full colour information. The original uncompressed
image data are therefore already less than true resolution, and minimal JPEG compression may not be degrading
the image quality to anything much below that already present in the original image data.

The training images come from a mobile eye-screening unit and the digital camera has to be removed from
the fundus camera so that it can be fitted in the van that is used for transport to remote various centres. Dust
unfortunately gets into the optics and cleaning is not straightforward. The training images therefore contain
dust marks, that may shift position or appear/disappear from images captured on one day to those captured on
another day. Dust marks can have a very similar appearance to microaneurysms that can be confounding even
to the expert eye. They represent a significant artefactual problem, that has been noted by other investigators
of digital imaging in ophthalmology.

The dust problem has been overcome in the following manner. For each patient at least four images (two
different fields of each eye) exist. We process all images of each patient with the preprocessing of microaneurysm
detection to the stage of generating the candidate microaneurysms (that is, the final Naïve Bayes classifier is not
run). These candidates include dust marks as it is virtually impossible to distinguish between microaneurysms
and circular dust marks using the green field information only. The candidate microaneurysm detections are
compared across all images of a patient, and if a majority of images contain a candidate at the same position in
the field-of-view then that candidate is marked as a dust mark. In this way dust patterns are generated for each
patient, and the final microaneurysm detections from the microaneurysm detector can be compared against the
dust patterns to remove false detections due to dust marks. All results presented are after all false detections
due to dust have been removed in this manner.

The training images were further compressed with the libjpeg software of the Independent JPEG Group
to 70%, 50%, 30% and 10% quality. The microaneurysm detector was then run on all training images of all
qualities. Diabetic retinopathy was predicted from the presence of microaneurysms in an image and tested with
the methodology of the bi-normal parametric model of ROC analysis. The area-under-curve (AUC) is used
as a measure of disease detection efficacy. Ninety-five percent confidence intervals are calculated on the AUCs
using the ROCKIT program.

It is desireable to test the effects of JPEG compression with images that have been captured at source at
original image quality (for example, saved as TIFF images with no image compression). Then a comparison
can be made between original image quality and JPEG compression. Furthermore a separate image set from
the training images is desireable to avoid the bias of classifier ‘over training’. To this end two sources who
could provide high resolution retinal images without any image compression were identified. Unfortunately,
close inspection of images from the source who provided the larger number of retinal images, revealed that the images
had been compressed, at some stage, with JPEG compression even though the images were provided in TIFF
format. The source claimed that the images had been saved in TIFF format without image compression directly
on image acquisition! This shows how difficult it can be to avoid JPEG compression in retinal imaging – the
client software claims to be using TIFF format but nevertheless, at some stage, uses JPEG compression, thus

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degrading image quality. The method used to reveal if images had been compressed at any stage with JPEG compression is described in the Appendix.

The ‘testing images’ dataset therefore contains twenty retinal images of 6 megapixel effective resolution, 12 images with confirmed diabetic retinopathy and 8 without retinopathy, obtained from the second source. When cropped to the fundus camera aperture the images have approximately 2400 × 2000 pixel resolution. The procedure listed in the Appendix was used to verify that these images had never been compressed with JPEG compression. These images do not contain dust marks so the dust mark identification procedure was not applied to them. The ability to detect diabetic retinopathy on these images, and after they have been compressed, was determined in the same manner as for the training images. We do not bother to calculate AUC confidence intervals as we admit, at the outset, that any useful statistical significance is not possible with such a small number of images.

5. RESULTS

Results were calculated on the training images at their original 95% quality and when they were further compressed to 70%, 50%, 30% and 10% quality. The JPEG qualities and the resultant mean compression ratio calculated over the 80 images (that were cropped to the fundus camera aperture), as are the compression ratios for the 20 testing images (also after cropping to the fundus camera aperture) are listed in Table 1.

The detection of a single microaneurysm in an image is used to classify the image as diseased. We assigned the rating of the image to be the highest likelihood (to be a microaneurysm) reported by the Naïve Bayes classifier for all candidates in the image. The resulting non-parametric ROC graph, using the ophthalmologist’s determined presence of diabetic retinopathy in the images as the gold standard, is shown in figure 1. To determine AUC values and 95% confidence intervals, bi-normal parametric ROC analysis using the ROCKIT24 program was applied. The resulting AUCs and 95% confidence intervals are listed in Table 2. This analysis was performed for the original 95% quality images, and for the images re-saved at 70%, 50%, 30% and 10% quality. When paired

![ROC: Predicting Retinopathy on JPEG Images](image-url)

Figure 1. Predicting retinopathy on the training images.
Table 1. JPEG compression ratios for various quality factors

<table>
<thead>
<tr>
<th>JPEG Quality</th>
<th>Compression Ratio</th>
<th>Training Images</th>
<th>Testing Images</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncompressed</td>
<td>–</td>
<td>1:1</td>
<td>1:1</td>
</tr>
<tr>
<td>95%</td>
<td>16:1</td>
<td>16:1</td>
<td>16:1</td>
</tr>
<tr>
<td>70%</td>
<td>67:1</td>
<td>78:1</td>
<td>78:1</td>
</tr>
<tr>
<td>50%</td>
<td>110:1</td>
<td>134:1</td>
<td>134:1</td>
</tr>
<tr>
<td>30%</td>
<td>190:1</td>
<td>216:1</td>
<td>216:1</td>
</tr>
<tr>
<td>10%</td>
<td>340:1</td>
<td>389:1</td>
<td>389:1</td>
</tr>
</tbody>
</table>

Table 2. AUC of automated retinopathy detection on the training images

<table>
<thead>
<tr>
<th>JPEG Quality</th>
<th>AUC</th>
<th>95% confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>95%</td>
<td>0.95</td>
<td>(0.87–0.99)</td>
</tr>
<tr>
<td>70%</td>
<td>0.97</td>
<td>(0.90–0.99)</td>
</tr>
<tr>
<td>50%</td>
<td>0.92</td>
<td>(0.84–0.96)</td>
</tr>
<tr>
<td>30%</td>
<td>0.84</td>
<td>(0.74–0.91)</td>
</tr>
<tr>
<td>10%</td>
<td>0.75</td>
<td>(0.62–0.86)</td>
</tr>
</tbody>
</table>

Tests of AUCs are analysed only AUCS of the 95% compared to 10% qualities, 70% to 30%, 70% to 10% and the 50% to 10% are significantly different at the 95% confidence level. The 95% to 30% and the 30% to 10% difference in AUCs barely missed significance at the 95% confidence level.

The non-parametric ROC graph determined for the 20 testing images is shown in figure 2. It demonstrates a similar behaviour as seen for the training images.

![ROC: Predicting Retinopathy on JPEG Compressed Images](image_url)

**Figure 2.** ROC for detecting retinopathy on testing images
6. DISCUSSION
The results show a general trend of worsening ability to predict the presence of diabetic retinopathy as images are compressed to smaller sizes. Compression at qualities of 95% and 70% show very little difference in ability to detect retinopathy over that of uncompressed images. Compression at 50% quality shows some minor decrease in AUC and in the ROC curves for both the training and testing image sets, however the difference in AUCs between 95% and 50% qualities did not achieve statistical significance. Further study with a larger number of images is needed to confirm this observation. If the AUC curves of the training image set are to believed then at 90% specificity the sensitivity drops from about 85–88% (for 95% quality) to about 73%–80% (for 50% quality). This may take the sensitivity for detecting retinopathy from being acceptable to unacceptable in an eye-screening programme.

If we take the 50% quality rating as the point where artefacts are having an unacceptable influence on automated diabetic retinopathy detection then images can be acceptably compressed to about 80:1 compression ratio (the largest compression ratio of the 70% quality images). Recall that this is for retinal images captured at approximately 6 megapixel (3000 × 2000 pixels) resolution before cropping to the fundus camera aperture. This compares favourably with studies focussed on manual grading of retinopathy by specialists. Those using images of insufficient resolution (below about 1300 × 1000 pixels) find that compression ratios as low as 30:1 are problematic\textsuperscript{11–13} whereas those that use good image resolution (around 3000 × 2000 pixels) find that compression ratios as high as 110:1 are acceptable\textsuperscript{16}.

The only previous study of relevance to investigate the effect of JPEG compression on automated microaneurysm detection is that of H"ansgen et al.\textsuperscript{18} They found that a 20:1 compression ratio was problematic for automated microaneurysm detection. This is possibly explained by the use of images of questionable resolution (1000 × 1000 pixels). It should also be noted that H"ansgen et al. were attempting a more difficult problem, namely of correctly identifying and locating all microaneurysms in an image, rather than predicting diabetic retinopathy based on the presence of microaneurysms.

7. CONCLUSION
The effect of JPEG compression on automated detection of diabetic retinopathy was studied. It was found that for 6 megapixel resolution images that compression ratios up to 80:1 (70% quality factor) could safely be sustained. Higher compression ratios (lower quality factors) lead to a decreasing AUC of the ROC curve and may not be acceptable for an eye-screening programme. Further study with a larger number of images is needed to confirm these results at an acceptable statistical significance.

8. ACKNOWLEDGEMENTS
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References


Appendix

Identifying the blockiness artefact of JPEG compression in images provides a relatively easy means to identify if images have been compressed with JPEG at any stage even if they are provided in some other image format. The discrete cosine transform used in JPEG compression is applied to each $8 \times 8$ block of pixels. This leads to substantially greater pixel errors at the edge of the blocks. We detect these errors by first calculating the pixel difference between neighbouring pixels along rows, that is, by calculating

$$d(i, j) = f(i + 1, j) - f(i, j)$$  \hspace{1cm} (1)

where $f(i, j)$ is the $(i, j)$ pixel of the intensity $f$ of the JPEG image. For evaluating retinal images we use the green plane of the colour as the intensity $f$. Then the column means $\bar{c}$ of the absolute values are calculated by

$$\bar{c}(i) = \frac{1}{N} \sum_j |d(i, j)|$$  \hspace{1cm} (2)

where there are $N$ rows in the image. A simple plot of $\bar{c}$ will reveal spikes at every eight positions if the image has ever been subjected to JPEG compression. Alternatively a discrete Fourier transform of $\bar{c}$ will reveal significantly extra energy in the bin of frequency corresponding to eight pixels if the image has been subject to JPEG compression. This is true even if the quantisation tables are all set to 1, that is, the best possible quality. Of course, this all assumes that the original true image does not contain a repeating thin structure (lines) separated by eight pixels across the whole image!