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Diagnostic accuracy of chest X-rays acquired using a digital camera for low-cost teleradiology

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Summary Store-and-forward telemedicine, using e-mail to send clinical data and digital images, offers a low-cost alternative for physicians in developing countries to obtain second opinions from specialists. To explore the potential usefulness of this technique, 91 chest X-ray images were photographed using a digital camera and a view box. Four independent readers (three radiologists and one pulmonologist) read two types of digital (JPEG and JPEG2000) and original film images and indicated their confidence in the presence of eight features known to be radiological indicators of tuberculosis (TB). The results were compared to a ''gold standard'' established by two different radiologists, and assessed using receiver operating characteristic (ROC) curve analysis. There was no statistical difference in the overall performance between the readings from the original films and both types of digital images. The size of JPEG2000 images was approximately 120KB, making this technique feasible for slow internet connections. Our preliminary results show the potential usefulness of this technique particularly for tuberculosis and lung disease, but further studies are required to refine its potential.

1. Introduction

Telemedicine has been proposed as a way to make medical expertise available in developing countries particularly in remote areas and where the few specialists are separated from most of the population. According to WHO Estimates of Health Personnel from 1998, there were 279 doctors per 100,000 population in the US, but only 56.3 doctors per 100,000 in South Africa, 93.2 per 100,000 in Peru and 13 in Haiti [1]. Fourteen countries in Africa do not have a single radiologist (1999), and in many others there are few radiologists in rural areas. Real-time interactive telemedicine, as used in many developed countries, is not generally feasible in developing countries because of lack of high-bandwidth networks and advanced

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equipment. Store-and-forward telemedicine is a simple technique in which a text description of the patient's condition and one or more digital images are sent as e-mail attachments. It offers a convenient and less expensive solution, since teleconsultation can be achieved with a dial-up internet account and without special equipment [2,3].

In South Africa the technique is used for referrals from remote clinics [4,5] and between university departments [6]. The US Armed Forces Institute of Pathology has made extensive use of e-mail and web-based techniques for telepathology [3], and a telepathology link has been established between hospitals in Italy [3]. A telemedicine link between hospitals in Bosnia and in UK is used by British Armed Forces [7]. Similar telemedicine links have provided specialist advice to physicians in Bangladesh, Nepal, the Solomon Islands [8], and in north west Russia [9]. Store-and-forward teledermatology has found widespread use in situations ranging from remote parts of Africa [4,10] to teaching hospitals in the US [11] and Europe [12,13]. Many users are sending images of X-rays acquired with a digital camera as a form of teleradiology, and initial studies have shown this technique to be adequate for many diagnoses [5,7,14—16]. The size of the e-mail attachments is a potential problem with this technique necessitating some form of image compression. Previous studies have analyzed the effect of X-ray image compression on diagnostic quality and provided evidence that even with high-levels of lossy compression adequate diagnostic quality for chest X-rays can be maintained under the right circumstances [17—21].

This study was designed to assess whether store-and-forward teleradiology using a widely available, low-cost digital camera is adequate for the detection of X-ray features of common respiratory diseases such as tuberculosis (TB) in developing countries. It builds on previous research by using receiver operating characteristics (ROC) analysis to compare the influence of two different image compression algorithms on radiologists' readings from digital camera-generated chest X-ray images.

2. Material and methods

2.1. Original analog image acquisition

Ninety-one upright posteroanterior chest X-ray images were selected for study. Forty radiographs were images selected from teaching files, all of which had detailed description of the radiology findings as well as the final diagnosis. Another 37 X-rays used in this study were accompanied by diagnoses and radiology reports. The remaining 23 images did not have detailed reports or diagnoses. Table 1 summarizes the images used in this study. The X-rays were selected based on the presence of features of varying subtlety deemed to be the most important for TB by TB specialists (E.N. and F.L.J). The infiltrates ranged from small areas to lobar pneumonia, cavities from about 1 to 3 cm in diameter, pneumothoraxes from 5% to total lung collapse, pleural effusion from slight blunting of costophrenic sulcus to effusions containing two or more liters of fluid, and nodules from about 5 mm in diameter granulomas to nodular opacities of about 2×2 cm in diameter. Some of the features such as lymphadenopathy and cavities were under represented. Some images had more than one feature. The coexistence of lymphadenopathy and lung disease lead to obscuration of lymph nodes and decreased the number of cases claimed for lymphadenopathy. The ''gold standard'' for the presence of several features for all the images was determined by two independent board-certified radiologists. If there was disagreement between the two, both features were included in the gold standard.

Table 1 Summary of the 91 X-ray images used in the study

X-ray feature	Number of occurrences
Infiltration/consolidation	33
Cavities	13
Pneumothorax	13
Lymphadenopathy	12
Pleural effusion	20
Calcifications	15
Scarring	27
Nodule or mass	31
Number of normal chest X-rays*	22
Number of TB cases	17

* X-rays not containing any of the features of interest.

2.2. Digital image acquisition

The study was designed to replicate as nearly as possible the practicalities of imaging X-rays in a developing world clinic, which may have only a simple X-ray machine and a view box or sunny window. This included the use of a modestly priced, battery-operated camera with minimal adjustment of the default settings. An Olympus C3000Z digital camera captured images of chest X-rays at a resolution of 2048×1536 pixels with 24-bit color depth which translates to 8-bit gray scale after conversion. Details of camera specifications are

Table 2 Specifications of Olympus C3000Z digital camera

Imager	1/1.8 in. CCD solid-state image pickup, 3.34 million pixels
Lens	Olympus multivariator zoom lens 6.5—19.5 mm F2.8-FII
Exposure control	Exposure compensation ±2 EV in 1/3 EV steps aperture priority
Focusing	IESP (intelligent electro selective pattern) TTL system autofocus, manual focus with focusing range: 0.2 m—∞
Viewfinder	Optical real-image viewfinder.
LCD monitor	4.5 cm/1.8 in. wider angle color TFT LCD monitor with 114,000 pixels

summarized in Table 2. All of the digital pictures of images were taken in the same darkened room. The images were placed on a standard lighted viewing box appropriate for viewing chest X-rays and photographed with the digital camera mounted on a tripod without flash. The tripod was placed approximately 30 in. from the viewing box. This distance was chosen to assure that most X-rays filled the camera's LCD monitor with the camera's optical zoom set to the midpoint. Minor optical zoom adjustments were made to accommodate different X-ray sizes. The camera's autofocus function was used throughout. Exposure compensation was set manually to 1.3 EV (discussed below). The shutter was operated using the camera's remote control to avoid movement artifacts. Two different types of digital images for each plain radiograph were obtained, one using the default setting (HQ JPEG) of 15:1 compression ratio, and one using the uncompressed TIFF setting. The JPEG compressed images were approximately 600KB in size while the TIFF images were 9MB. The Olympus C3000Z was chosen as it had good image resolution for its time and excellent reviews for image quality [22]. Other good quality cameras with equivalent or better resolution and a good lens should be suitable. A web site is available that allows detailed comparison of images from a range of digital cameras including the Olympus C3000Z [23].

2.3. Preliminary study

A preliminary study was conducted to verify appropriate digital camera settings because the relatively bright mediastinum in chest X-rays usually causes auto exposure systems to under-expose the lung fields. Images of the first 25 cases were taken using the default HQ JPEG compression.

The images had five different exposure compensation levels: 0.0 EV (default setting), −0.3 EV (underexposure), and 0.7 EV, 1.3 EV, and 1.7 EV (overexposure). Four independent readers blinded to the compression level read the X-rays and chose one best image, assessed as the image that showed the clearest detail in the lung fields. Exposure compensation of 1.3 EV (overexposure) was chosen in 58%, 1.7 EV in 20%, 0.7 EV in 15%, 0.0 EV in 5%, and −0.3 EV in 2% of cases. Therefore, the median value of 1.3 EV exposure compensation was further used in all, but seven bright original images, in which 0.7 EV was used.

2.4. Image conversion

The 600K JPEG-compressed images were rotated if necessary, cropped, and converted to gray-scale using Adobe Photoshop® software. The final file size after image conversion was about 400KB. In developing-world clinics these steps can be done using free TeleMedMail [24] software developed by two of the authors (D.J. and H.S.F) which is available at http://www.sourceforge.net/projects/telemedmail.

JPEG2000 images could not be generated directly from the camera and so were generated from the uncompressed TIFF images using JJ2000 Java software. The TIFF images were converted to Portable Pixel Map (PPM) images,[1] which were then compressed at a 60:1 rate using the JPEG2000 compression algorithm. For images that were rotated, cropped, and converted to gray scale first the resulting file size was between 98 and 120KB. For the final viewing, the images were decompressed back to PPM. The use of lossless conversion through the PPM format was necessary because the viewer used in this study does not currently read JPEG2000 files. The use of PPM should not affect the study results because the files went through the JPEG2000 compression process, and the other manipulation steps needed to view the file are lossless and, therefore, do not affect the image quality.

[1] This step was required because the JPEG2000 compatible compression software does not currently support TIFF images. For this conversion, IrfanView 3.1® software was used. This software is freely available from http://stud1.tuwien.ac.at.~9227474/english.htm.

2.5. Image compression algorithms

JPEG image compression is designed to accommodate limitations of the human eye. Small color changes are perceived less accurately by humans than small changes in brightness. JPEG compression provides both lossless and lossy compression. The JPEG compression algorithm has three steps: transformation, quantization, and encoding. The quantization step is the only one in which information is lost. The image is divided into 8×8 pixel blocks and each block is transformed separately using the discrete cosine transform (DCT) algorithm. At low-ratio JPEG compression is ''visually lossless,'' mainly removing high-frequency noise [25]. Readers generally prefer radiographic images with some degree of compression, which removes the ''salt-and-pepper'' noise [19,25,26]. Very high-compression ratios produce blurring and artifacts including a ''blocking effect'' and a ''line pattern'' effect due to the initial decomposing of the image into 8×8 pixel blocks [18].

Wavelet image compression techniques can greatly reduce file sizes while preserving quality relative to the JPEG standard [27]. The transformation is performed over the entire image using the Discrete Wavelet Transform (DWT) instead of on separate 8×8 pixel blocks. Typically two high- and two low-pass filters split the image into two sub-bands in each direction. The JPEG2000 wavelet-compression algorithm has additional advantages over the old JPEG standard, such as allowing a much wider dynamic range of up to 16 bit/pixel image depth.

2.6. Viewing of the images

An image viewer was distributed on the same CD as the digital images to assure that all readers used the same viewing software. The viewer is part of the TeleMedMail software [24]. The viewer allows the readers to move back and forward between images, zoom, and adjust window levels.

Readers were instructed not to use laptop or LCD monitors because some did not properly display the full dynamic range of images in our initial tests. All readers used color CRT monitors with Reader 1 using a 17 in., Readers 2 and 3—a 19 in., and Reader 4—a 15 in. monitor. The monitors were optimized for gray-scale using a gray-scale test pattern provided with the images on the same CD [28,29]. All readers also got detailed instructions explaining the use of the viewing software as well as how to set up the monitor using the gray-scale test pattern provided. The viewing time for each image was not controlled, to better reflect conditions in real clinical radiology practice.

2.7. Data collection

Four independent readers blinded to patients' identification and image compression evaluated the JPEG, JPEG2000, and original analog images. Of four readers, three were board-certified radiologists each with approximately 15 years experience in radiology, and one was a pulmonologist, with 25 years of experience, specialized in TB. The images were presented to the readers in batches of 18—26 with a 2 week forgetting interval between batches. Each batch was of a single image type, except for the pulmonologist's, to whom, for logistic reasons, the JPEG and JEPG2000 versions were presented together in random order. Three of the readers assessed JPEG2000 images. Reader 1 read 26, Reader 2 read 24, Reader 3 read 25, and Reader 4 read 18 images. Due to availability issues, Reader 1 assessed JPEG2000 version of images for which original and JPEG images were read by Reader 2. Table 3 summarizes the study design.

The readers completed the questionnaire indicating the presence or absence of the eight chest X-ray TB indicators given in Table 1. They recorded the degree of their confidence in the presence of each indicator using a five-point ordinal scale (1, definitely present; 2, probably present; 3, can not decide; 4, probably absent; 5, definitely absent). They also recorded their perception of the image exposure and diagnostic quality using a three-point ordinal scale (1, good; 2, adequate; and 3, poor).

2.8. Statistical analysis

Receiver operating characteristic curve analysis was performed. This method of comparison utilizes the ROC curve, which takes into account the effect on metrics such as sensitivity and specificity

Table 3 Summary of the images read by particular readers

Reader	Image number		
	Plain images	JPEG images	JPEG2000 images
1	1-25	1-25	1-49
2	26-49	26-49	NA
3	50-72, 11, 41	50-72, 11, 41	50-72, 11, 41
4	73-91	73-91	73-91

of different thresholds applied to the outcome variable. Instead of the reader classifying the indicator as being present or absent, she gives a rating of her certainty of its presence. This scale can then be mapped into the presence/absence space differently, depending on which threshold is used to differentiate ''presence'' from ''absence''. A threshold that requires more certainty of the presence of a feature will classify few observations as ''present,'' so the sensitivity will tend to be low, but the specificity will tend to be high. An ROC curve is created by plotting sensitivity against 1—specificity for a range of thresholds. The area under the curve (AUC) is used as a summary of the discrimination ability of the diagnostic test. The results presented here use the Hanley—McNeil standard error correction method for comparing ROC areas generated by readings of different compressions of the same images [30].

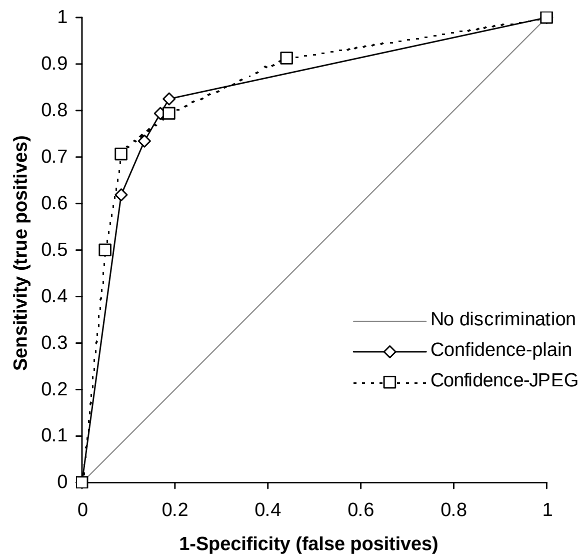

Fig. 1 Receiver operating characteristics (ROC) curves for plain and JPEG images for infiltration/consolidation.

3. Results

The results of the feature-by-feature analysis of plain and JPEG images, when the data from all readers were pooled, are summarized in Table 4. All the *P*-values were computed using the Hanley—McNeil method. The main finding is that the only feature in which the readings produce significant difference between AUCs is ''calcification''.

Fig. 1 shows ROC curves for plain and JPEG images when all the features were included in analysis.

The results for JPEG2000 images are summarized in Table 5. There are no statistically significant differences between readings of plain images and JPEG2000-compressed images.

Table 4 Comparison of plain and JPEG images per feature

Feature	AUC plain images	AUC JPEG images	Difference	*P*-value
Infiltration/consolidation	0.842	0.861	−0.019	0.6349
Cavities	0.907	0.892	0.015	0.8367
Pneumothorax	0.922	0.911	0.012	0.8408
Lymphadenopathy	0.710	0.741	−0.030	0.7340
Pleural effusion	0.789	0.891	−0.102	0.1276
Calcifications	0.779	0.938	−0.159	0.0297
Scarring	0.766	0.736	0.030	0.5580
Nodule or mass	0.863	0.855	0.008	0.8426

Table 5 Comparison of plain and JPEG2000 images per feature

Feature	AUC plain images	AUC JPEG 2000 images	Difference	*P*-value
Infiltration/consolidation	0.842	0.854	−0.012	0.7951
Cavities	0.907	0.834	0.074	0.3489
Pneumothorax	0.922	0.859	0.063	0.3839
Lymphadenopathy	0.710	0.710	0.000	1.0000
Pleural effusion	0.789	0.850	−0.061	0.4204
Calcifications	0.779	0.831	−0.052	0.4926
Scarring	0.766	0.730	0.037	0.5797
Nodule or mass	0.863	0.832	0.031	0.5094

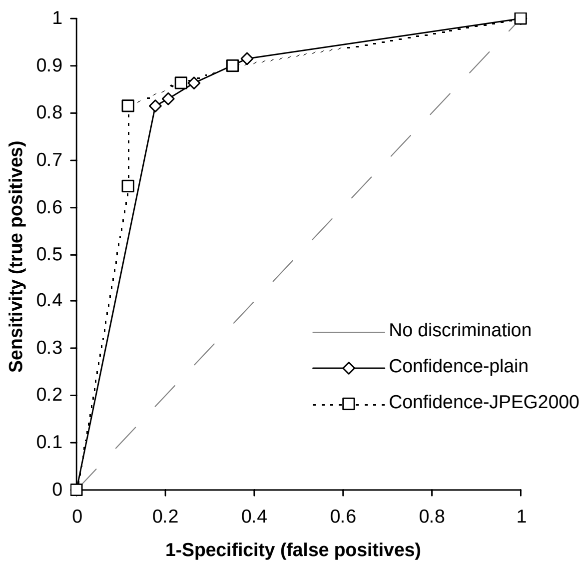

Fig. 2 Receiver operating characteristics (ROC) curves for plain and JPEG2000 images for infiltration/consolidation.

Fig. 2 shows ROC curves for plain and JPEG2000 images when all the features were included in analysis.

We also performed concordance analysis that revealed no significant differences between readings of plain images and both types of compressed images (results not shown).

4. Discussion

TB as a public health concern in the developing world may justify the use of digital cameras for consultations regarding radiography. A potentially significant finding in this work, that calcifications can become more visible due to the overexposure inherent in optimizing the visualization of lungs, is itself a benefit in confirming prior exposure to tuberculosis. This, combined with the ability to demonstrate striking findings adequately to support a clinical dialog, brings to healthcare workers in the most remote locations, the opportunity to have consultation with pulmonologists, infectious disease specialists, and radiologists.

Some interactive real-time telemedicine and teleradiology systems have been shown to provide useful advice as well as training opportunity to doctors in remote settings in industrialized countries [31]. Real-time videoconferencing has the advantage of allowing the patient to interact with the distant physician. Requests by the specialist for additional information can be fulfilled immediately. However, the high costs of equipment, high-bandwidth requirements, and network unreliability limit their use in developing countries.

Compared to real-time teleradiology, store-and-forward teleradiology offers a more practical and less expensive solution. Store-and-forward methods allow the use of low-cost equipment, low-bandwidth connectivity, and asynchronous consultation. This approach is successfully used in industrialized countries where high-quality radiographic images are sent over telemedicine networks for consultation [31]. The size of a standard DICOM images is large, however, requiring fast and reliable connections, which may not be feasible, even in some areas of developed countries. The way to decrease the transmission time for a given transmission rate is to reduce the file size by image compression.

The effect of image compression on chest X-ray images quality has been discussed in previous studies. Aberle and Gleeson [21] used their own compression algorithm based on discrete cosine transform (DCT) and found a compression ratio of 20:1 acceptable for chest X-rays. Savcenko et al. [17] concluded that wavelet compression of 80:1 decreased the ability to detect studied features, but 40:1 did not. Erickson and co-workers [19] found that 40:1 wavelet compression did not decrease the perceptibility of 11 anatomic structures of interest. All those studies used scanners or film digitizers for generating the digitized images.

Recently, digital cameras have emerged as an efficient method of obtaining digital images. Krupinski et al. [32,33] evaluated the effectiveness of digital photography for dermatology and bone trauma diagnoses and found digital camera-generated images to be of sufficient diagnostic quality. Piccolo et al. [13,34] found high- diagnostic concordance between telepathology and histopathologic diagnosis. Lim et al. [35] and High et al. [36] evaluated a digital camera for teledermatology and also found high-concordance with faceto-face diagnoses.

Ruess et al. [37] evaluated three modalities for digitizing thoracic images: film digitizer, flatbed scanner, and digital camera. In contrast to this study, they found digital camera's images to be inferior to hard-copy and flatbed scanner images, but not to film digitizer images. However, the resolution of digital camera used in the study was much lower than in this study (1.6 megapixel versus 3.3 megapixel) and the size of the camera-generated images was altered to match images generated by the image digitizer (400 pixels high), which would be expected to greatly affect image quality.

Corr et al. [5] conducted a pilot study in which 100 digital camera-generated X-ray images (1 megapixel Sony camera) were e-mailed to verify diagnoses using remote consultation, and found a high-degree of agreement between the diagnoses.

While digital cameras are generally more convenient than digital scanners, there are some known limitations. Whitehouse and Moulding [38] compared two digital cameras with a dedicated radiographic film scanner. They found that the digital cameras had lower latitude and higher image noise than the digital scanner. Whether these differences are significant may depend on the exact nature of the image being digitized since the differences vary over the optical density range.

This project is a continuation of previous research that used digital cameras, but the focus is on the statistical analysis of the difference in quality between the digital images compressed using two different compression algorithms and the original plain film images. Furthermore, this project focuses on specific features thought to be important in diagnosis of TB. Understanding the effects of digitization and compression algorithms at the feature level allows us to clarify whether there are deficiencies that may reduce the diagnostic accuracy of certain clinical conditions.

Using ROC analysis, there was no statistically significant difference between plain images and two types of digital images: JPEG and JPEG2000 except for calcifications, in which AUCs for JPEGs were significantly higher. This finding could be due to chance, as it was most noticeable with one reader. On the other hand it is possible that some of the features are easier to detect in the JPEG version due to the overexposure of the images during the digitization. High-density features such as calcifications that are bright on the original analog images are expected to be enhanced in the overexposed images.

One of the limitations of the study was the use of a non-homogeneous case mix. The images were of different quality and exposure, and 16 plain film images were assessed as having poor diagnostic quality by the readers. However, this may be representative of the variable quality of radiographs in developing countries. Other limitations include underrepresentation of some features and small number of readers. The restricted dynamic range of the images (8 bit/pixel versus 10 bit/pixel as recommended by ACR [39]) is a limitation for contrasty images. Exposure compensation to optimize the most important areas of the image (such as lung fields or bones) may partially overcome this problem, in difficult cases two images may be taken at different brightness levels.

It is important to note that the results described here may not be reproduced without careful photographic technique, in particular in focusing and use of a tripod. Also the digital camera used (Olympus C3000Z) is noted for its good lens and excellent overall image quality [22]. In purchasing a camera it is advisable to check published reviews of image quality and use adequate resolution (3.3 megapixels), though general image quality has improved substantially in the 4 years since that camera was developed.

5. Conclusion

This study used ROC curve analysis to evaluate whether photographing chest X-rays with digital camera, with specifications similar to or better than the one used here, allows reliable detection of features commonly used in diagnosing TB. It provides a basis for future research on assessing the usefulness of the technique of low-cost teleradiology. The results indicate that both JPEG- and JPEG2000-compressed images from the camera allow readings of sufficient quality for the diagnosis of tuberculosis. The JPEG2000 findings are particularly interesting because the image size is approximately 40% the size of JPEG images and the performance is not statistically different from that of the original analog images (Table 5). Small file size is an important priority in countries that have only unstable dialup Internet connectivity, and are frequently limited to less than 16,000 kbit/s even in South Africa (H. Fraser personal communication). The 60:1 compression ratio used in this study was based on results of previous studies in which scanners were used to digitize images; the ideal ratio has yet to be determined. Cameras are now available with 5 or 6 megapixel resolution, but as the American College of Radiology [39] recommendations call for 4 megapixels for chest X-rays, this higher resolution may not be necessary and will increase file size. As of November 2001 the National Electrical Manufacturers Association (NEMA) has added the JPEG2000 standard to the Digital Imaging and Communications in Medicine (DICOM) standard for compressing medical images [40]. It supports a wider dynamic range (12 bit/pixel), which should reduce the problem of finding optimal exposure setting for high contrast images experienced in this study. Since cameras using JPEG2000 compression will reach the market in the near future, this study provides evidence that they can be successfully used for digitizing chest X-ray images in resource-poor settings. At present, cameras that can export uncompressed TIFF images may be used with custom software to compress the images with wavelet algorithm (but only professional cameras can currently save images at greater than 8 bit dynamic range).

Further study is needed, using a broader case mix for each feature, involving more readers, and using stricter criteria for determining the presence of findings. A direct comparison between a digital camera and a low-cost scanner using wavelet compression would also be valuable.

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