High-Resolution Digital Teleradiology: A Perspective

Gopinath R. Kuduvalli, Rangaraj M. Rangayyan, and J.E. Leo Desautels

Teleradiology has come a long way, from analog transmission systems using slow-scan television over standard telephone lines, to present-day, commercially available, microcomputer-based, low-resolution teleradiology systems. However, there exists a need to address the high-resolution end of the medical imaging categories, namely chest radiographs and mammograms, to firmly establish teleradiology. The availability of high-resolution image digitizers, display units, and digital hard copiers has made high-resolution digital teleradiology a feasible concept. Although the use of satellite channels can speed up the transmission of radiographic image data, with widespread acceptance of high-resolution teleradiology systems in the foreseeable future, the sheer amount of data involved in this field will give rise to problems of data transmission and storage. Data compression schemes can bring down the amount of data handled and can have a great economic impact on future teleradiology systems. We have developed a number of compression techniques for reversible compression of medical images. Our experiments have shown that lossless compression of the order of 4:1 is possible for a class of high-resolution medical images. Use of pattern recognition techniques offers the potential to bring down these data rates even further. We plan to use these techniques in a prototype high-resolution teleradiology system being developed. In this paper, we trace some of the developments in teleradiology and image data compression, and present a perspective for teleradiology in the 1990s.

KEY WORDS: **teleradiology, image coding, data compression, image transmission.**

TELERADIOLOGY is defined as the practice of radiology at a distance.[1,2] Teleradiology offers a technologic approach to the problem of eliminating the delay in securing consultation of a radiologist to patients in rural and remote areas. Timely availability of radiologic diagnoses via telecommunication could potentially reduce morbidity and mortality of people in remotely situated areas and in developing countries, and costs of transportation to tertiary health-care centers. In the military environment, where one study in the United States in 1983[3] indicated that over 65% of the medical facilities with radiographic equipment have no radiologists assigned to them and an additional 15% have only one radiologist, teleradiology is an ideal vehicle for redistributing the image-reading work load from understaffed sites to more adequately staffed central locations.[4] The province of Alberta, Canada, has 130 health-care centers with radiologic imaging facilities; only 30 have resident radiologists. Sixty-one of the other centers depend on visiting radiologists. The remaining 39 centers send their radiographs to other centers for interpretation, with a 3- to 14-day delay in receiving the results.[5] The situation is comparable in the neighboring provinces of Saskatchewan and Manitoba. These three provinces could benefit significantly from teleradiology. Even in the case of areas served by contract radiologists, teleradiology would permit evaluation and consultation by competent radiologists in tertiary health-care centers in emergency situations as well as in complicated cases.

Early attempts at teleradiology systems[6,7] consisted of analog transmission of slow-scan television over existing telephone lines, ultra-high frequency (UHF) radiolinks, and other such analog channels.[2] Analog transmission and the concomitant slow transmission rates were entirely satisfactory for low-resolution images, such as nuclear medicine images. However, the transmission times were prohibitively high for higher resolution images, such as chest radiographs.[2] Further, the quality of images received with analog transmission is a function of distance, which results in an unpredictable performance of radiologists with the received images. Thus, the natural progression of teleradiology systems was toward digital image formats. The initial choice of a transmission medium was again the ordinary telephone line operating at 300 bits per second (bps) to 1,200 bps. Many of the commercially available teleradiology sys-

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From the Department of Electrical and Computer Engineering, The University of Calgary, and the Department of Radiological Sciences and Diagnostic Imaging, Foothills Hospital, Calgary, Alberta, Canada.

Supported by grants from the Natural Sciences and Engineering Research Council of Canada.

Address reprint requests to Dr R.M. Rangayyan, Department of Electrical and Computer Engineering, The University of Calgary, Calgary, Alberta T2N 1N4, Canada.

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tems still use telephone lines for transmission. Recent improvements in modem technology, allowing speeds up to 19.2 Kbps over standard telephone lines, and the establishment of a number of 56-Kbps lines for commercial use by telephone companies, have made this medium a viable one for low-resolution images.[8]

A major reason for users' reluctance in accepting teleradiology systems has been the inability to meet the resolution of the original film image with the digitized and received images. This has been so, for example, for mammograms and chest radiographs. Even a spatial resolution of 2,048 × 2,048 cannot capture the submillimeter features on these images.[9] Thus, a spatial resolution of 4,096 × 4,096 pixels or better, and at least 1,024 shades of gray, are required to capture all the diagnostic information on these images. The recent development of high-resolution digitizers capable of digitizing to a spatial resolution of 4,096 × 4,096 pixels with 4,096 shades of gray (12 bits) has alleviated this problem. But now, teleradiology system designers are faced with the problem of dealing with the immense amount of data involved in such high-resolution images. Transmission of such large amounts of data over ordinary telephone lines involves large delays,[2] and can be overcome to some extent by using parallel dial-up lines for increased data transfer rate. Even if the use of satellite channels can speed up their transmission,[10] the anticipated widespread acceptance of high-resolution teleradiology systems in the foreseeable future will create archival and image data management problems. This is the motivation for looking into data compression techniques. However, having gone a considerable length to obtain high-resolution images, any loss of information in compression and decompression which could result in possible degradation of performance of radiologists with those images and should be avoided.

Significant image data compression may be achieved by decorrelation of or reduction in redundancy in the image data. Redundancy in an image depends on the nature of the image and spatial resolution or scale of digitization, among other factors. Lossless compression of the order of 4:1 is possible on a class of high-resolution medical images, decreasing the transmission and storage requirements by the same factor.[11] Further, medical images such as chest and skull radiographs at times have regions surrounding the central image that do not carry significant diagnostic information. In the past, binary masks and predefined boundaries at a certain scale of digitization have been used for eliminating such regions from coding.[12,13] Moreover, in some medical images, only certain features are required for certain kinds of diagnosis: for example, in the case of chest radiographs, only the lung tissue might be of interest for certain types of diagnosis. In recent years, attempts have been made to model images using scene analysis techniques[14,15] for data compression. They have been studied under the name analysis-synthesis methods. A combination of scene analysis techniques with decorrelation methods can be used for extracting only those regions of the image that are of interest, and to encode these regions with no loss of quality. An integrated image analysis and compression system would be at the heart of a future teleradiology terminal. In this paper, we trace some of these developments and present a perspective for teleradiology in the 1990s.

HISTORICAL BACKGROUND

The first instance of transmitting picture information for medical diagnosis dates back to 1950 when Gershon-Cohen and Cooley used existing telephone lines and a facsimile system adapted to convert medical images into video signals for transmitting images between two hospitals 45 km apart in Philadelphia.[16] In a pioneering work in 1959, Jutras[17] conducted what is perhaps the first teleradiology trial by interlinking two hospitals 8 km apart in Montreal with a coaxial cable link to transmit telefluoroscopy examinations. The potential of teleradiology for securing consultation of a radiologist in remotely situated areas, and redistribution of radiologists' load from understaffed centers to more adequately staffed centers, was immediately recognized, and a number of clinical evaluation projects got underway.[2,6,7,18-23] Most of the early attempts consisted of analog transmission of medical images via standard telephone lines, dedicated coaxial cables, UHF radio, microwave, and satellite channels, and display on television monitors at the receiving terminal. James et al.[23] give an excellent review of the results of the early experiments. Andrus and Bird[1] describe a conceptual teleradiology system in which the radiologist, stationed at a faraway medical center, remotely controls a video camera to zoom in on selected areas of interest and observes the results in real time on a television screen. Steckel[24] conducted experiments with such a system using an 875-line, closed-circuit television system for transmitting radiographic images within a hospital for educational purposes, and concluded that the system's utility far outweighed disadvantages, such as the inability to view a sequence of images belonging to a single study.

In 1972, Webber and Corbus[6] used existing telephone lines and slow-scan television for transmitting ordinary radiographs and nuclear medicine images. The resolution achieved was entirely satisfactory for nuclear medicine images, but both the spatial resolution and the gray scale dynamic range (radiometric resolution) were found to be grossly inadequate for ordinary radiographs. A somewhat similar experiment using telephone lines and slow-scan television by Jelasco et al[7] resulted in 80% correct interpretation of radiographs. Other experiments with slow-scan television over telephone lines[23] demonstrated the inadequacy of this medium, and that the diagnostic accuracy in such a scheme was a function of the nature of the images being diagnosed.

Webber et al[20] used UHF radiotransmission links in 1973 for transmitting nuclear medicine images and radiographs. Whereas the system worked satisfactorily for nuclear medicine images, evaluation of chest films needed zoom and contrast manipulation of the television monitor. Murphy et al[19] used a microwave link for transmission of images of chest radiographs acquired with a remotely controlled video camera, over a distance of about 4 km, and concluded that this is an acceptable method for providing health care to those in remote areas.

Andrus et al[18] transmitted images of abdomen, chest, bone, and skull radiographs over a 45-km round loop, using a 4-MHz, 512-line television channel including three repeater stations. The television camera was remotely controlled using push buttons and a joystick to control zoom, aperture, focus, and pointing of the camera. They concluded that the television interpretations were of acceptable accuracy. Such real-time operation calls for special skills on the part of the radiologist, as well as coordination between the operator at the image acquisition site and the radiologist at the receiving center. Moreover, practical microwave links exist only between and within major cities, and cannot serve the communication needs of teleradiology terminals in rural and remote areas. Further, operating costs over the duration of interactive manipulations could be high and render such a scheme uneconomical.

In 1973, Lester et al[21] used the ATS-1 satellite for analog transmission of videotaped radiologic information, and concluded that satisfactory radiographic transmission is clearly possible "if a satisfactory sensor of radiographic images were constructed." In 1979, Carey et al[22] reported on the results of an analog teleradiology experiment using the Hermes spacecraft. They reported the effectiveness of television fluoroscopy to be 90% of that with conventional film. Page et al[25] used a two-way analog television network using the Canadian satellite ANIK-B to transmit radiographic images from northern Quebec to Montreal, and reported an initial accuracy in television interpretations of 81% with respect to film reading. This value reached 94% after a 3-month training of the participant radiologists in the use of the television system. The noise associated with analog transmission, the low resolution of the then-existing television monitors, and the requirement of radiologists to participate in real-time control of the image acquisition cameras made the concept of television transmission of radiographic images unacceptable. Further, the noise associated with analog transmission is distance dependent. Not surprisingly, James et al[23] reported that their teleradiology system, transmitting emergency department radiographs via a satellite channel from a local television studio, was unacceptable due to the decrease in accuracy of image reading to 85% to 86% with respect to standard radiographs.

DIGITAL TELERADIOLOGY AND THE STATE OF THE ART

Given the many advantages of digital communication over analog methods,[26] the natural progression of teleradiology was toward using digital techniques. The advent of a number of digital medical imaging modalities facilitated this trend.[27,28] Digital imaging also allowed for image processing, enhancement, contrast scaling, and flexible manipulation of images on the display monitors after acquisition. Many of the initial attempts[8,29-33] at digital teleradiology were based on microcomputers and used low-resolution digitization, display, and hard copiers. The resolution was on the order of 256 × 256 to 512 × 512 pixels with 256 shades of gray, mostly because of the nonavailability of high-resolution equipment. Gayler et al[29] describe a laboratory evaluation of such a microcomputer-based teleradiology system. They used a 512 × 512 × 8-bit pixel format for image acquisition and display, and evaluated radiologists' performance on routine radiographs. They found the performance to be significantly worse than that using film radiographs. Nevertheless, they concluded that microcomputer-based teleradiology systems "warrant further evaluation in a clinical environment."

In 1982, Rasmussen et al[33] compared the performance of radiologists on images transmitted by analog and digital means with light-box viewing of films. The resolution of digitization used was 512 × 256, with 6-bit pixels. The digital images were converted to analog signals for analog transmission. They concluded that the resolution used would provide satisfactory radiographic images for gross pathologic disorders, but would require higher resolution for subtle findings.

Gitlin et al[31,32] followed their laboratory evaluation[29] with a field trial using 9,600-baud standard telephone lines for transmission of 512 × 512 × 8-bit images from five medical care facilities to a central hospital in Maryland.[34] They reported[32] a relative accuracy of 96.7% with video image readings compared with standard film interpretations—a substantially higher percentage than laboratory studies[29]—and attributed the results to the large percentage of normal patients used in the sample, and to the higher clinical radiological experience of the video readers.

The 1984 field trial by Gitlin's group[31] used a 1,024 × 1,024 matrix of pixels, 9,600-baud telephone lines, and lossy data compression to bring down the transmission times. They observed a relative accuracy of video readings of 87% with respect to standard film readings. The relative accuracy was clearly a function of the type of data compression used, among other factors.

Gordon et al[35] present an analysis of a number of scenarios and tradeoffs for practical implementations of digital teleradiology. In related papers[36,37] they further discuss the potential for providing advanced imaging services such as computed tomography through teleradiology.

In 1987, DiSantis et al[38] digitized excretory urographs to 1,024 × 1,024-pixel matrices, transmitted them over standard telephone lines after data compression to a receiving unit approximately 3 km away, and used a panel of three radiologists to read the video images and compare them with the original film readings performed about a week earlier. Agreement of 93% was found between film and video readings in the diagnosis of obstructions. However, only 64% of urethral calculi detected in the original radiographs were detected in the video images. This demonstrated clearly that whereas a resolution of 1,024 × 1,024 pixels is adequate for certain types of diagnosis, higher resolution is required for capturing all the diagnostic information on the original film.

In 1987, Kagetsu et al[30] reported on the performance of a commercially available teleradiology system using 512 × 512 × 8-bit images and transmission over 9,600-baud standard telephone lines after 2.5:1 compression. They conducted experiments with a wide variety of radiographs over a 4-month period, and reported an overall accuracy of 89% between film and video display. Based on these studies, they recommended a review of original films at some later date because of the superior spatial and contrast resolution of film.

A large number of present-day, commercial teleradiology systems are microcomputer-based, and use existing telephone lines for transmission of image data. Recent improvements in modem technology leading to 14.4 Kbps and 19.2 Kbps transmission over standard telephones, and the installation of a number of 56 Kbps lines by telephone companies have improved this medium to some extent. The typical resolution of these low-resolution teleradiology systems is in the range of 256 × 256 to 512 × 512 × 8-bit pixels.[39-41] Some of the systems make use of lossy or lossless compression[41,42] to meet data rate limitations of standard telephone lines. Some vendors are supplying image compression hardware for building into available teleradiology systems.[43,44] Whereas such systems are adequate for handling the lower resolution of computed tomography, magnetic resonance, and nuclear medicine images, they are not suitable for handling the large format images such as chest radiographs and mammograms. Experiments with such systems have demonstrated the inadequacy of low-resolution digital teleradiology systems as an alternative to physical transportation of films/patients to centers with better radiological diagnostic facilities. Higher resolution is clearly called for and would result in larger amounts of data. Further, lossy data compression schemes to remain within the data rate limitation of telephone lines are clearly unacceptable.

The development of high-resolution image digitizers and display equipment, and routine utilization of high data-rate communication media, have paved the way for high-resolution digital teleradiology. In 1989, Carey et al[10] reported on the performance of the commercially available DTR-2000 teleradiology system from DuPont, consisting of a 1,684 × 2,048-pixel laser digitizer with 4,096 quantization levels, a T1 satellite transmission channel (1.544 Mbps), and a DuPont laser film recorder with 256 possible shades of gray. DuPont uses a nonlinear mapping from the original 4,096 quantization levels to 256 levels on the film hard copy to make use of the fact that the eye is more sensitive to contrast variations at lower density. With this mapping, at the lower end of the gray scale, small differences in gray values correspond to larger differences in optical densities than at the higher end of the gray scale. Thus, the overall optical density of the film is much larger than can be obtained by linear mapping. Carey et al[10] transmitted radiographic and ultrasonographic images over the system from Seaforth to London, Ontario, and reported an accuracy of 98% in reading laser-sensitive film. They concluded that the laser-sensitive film "clearly duplicated the original film findings." However, they also reported what they termed as contouring on the laser-sensitive film, which might have been due to the nonlinear mapping of the 4,096 original gray levels to 256 levels on the film. The problem with the nonlinear mapping is that certain portions of the original gray scale with rapidly changing gray levels are mapped into a single optical density on the film, giving rise to contouring artifacts.

Barnes et al[8] suggested that the challenge of integrating the increasing number of medical imaging technologies can be met by networked multimodality imaging workstations. Cox et al[45] made a comparison of images digitized to 2,048 × 2,048 × 12 bits displayed on monitors with 2,560 × 2,048 × 8-bit pixels, and digital laser film recording with conventional film. They reported significant differences in the performance of the three display formats: the digital hard copy performed as well as or better than conventional film, whereas the interactive display failed to match the performance of the other two. They suggested that although the differences could be eliminated by training the personnel in reading from displays, and by image enhancement techniques, it is premature to reach any conclusions.

A number of present-day, commercially available systems are approaching the resolution requirements of high-resolution digital teleradiology. The FilmFax teleradiology system from Discovery Systems Inc[46] makes use of a laser film scanner with a resolution of 2,481 × 2,048 × 12-bit pixels and transmission over telephone lines to a receiving terminal with a laser film recorder and a high-resolution display monitor with 2,048 pixels/scanline. The resolution of the laser film recorder is not advertised. In addition to digitized films, the FilmFax teleradiology terminal can accept data from computed tomography, magnetic resonance imaging, and other digital medical imaging modalities.

An improved version of DuPont's DTR-2000 Digital Teleradiography System[47] consists of a laser digitizer with a resolution of better than 4,000 × 5,000 × 12-bit pixels, a laser film recorder with a spatial resolution of 200 lines/mm, and a customized look-up table for mapping the 12-bit digital image data to 256 shades of gray on the laser film. The transmission is at a maximum rate of 1.544 Mbps over leased microwave links, coaxial cables, fiber-optic cables, or

T1 satellite channels, depending on the distance. DuPont has also recently announced the availability of optical disks, alleviating the problem of image archival to some extent.

The Vortech Image Transmission Network from Vortech Data Inc[48] uses DuPont's laser digitizer with a resolution of 1,684 × 2,048 × 12-bit pixels and satellite transmission at 1.544 Mbps. Their proprietary Medical Imaging Gateway (MIG) accepts the digital data, performs 2.5:1 lossless compression, transmits the data over a satellite channel, and is interfaceable to a number of standard digital medical imaging modalities. Optional ACR-NEMA interface[49] is available for interfacing the MIG to other imaging systems.

Batnitzky et al[50] have made an assessment of currently available technologies for film digitization, display, generation of hard copy, and data communication for application in teleradiology systems. They conclude that the currently available 2,048 × 2,048 × 12-bit laser digitizers, displays with 1,024 to 2,048, 8-bit to 12-bit pixels per scan line, hard copiers that interpolate 2,048 × 2,048-pixel matrices to 4,096 × 4,096-pixel matrices, and the merger of computer and communication technologies resulting in flexible wide-area networks, have paved the way for acceptance of "final interpretation teleradiology," completely eliminating the need to go back to the original films. Gillespy et al[51] described the installation of a DuPont Clinical Review System (CRS), consisting of a 1,680 × 2,048 × 12-bit pixel laser digitizer, and a 1,024 × 840 × 12-bit display unit, and report that "clinicians were generally satisfied with the unit." Studies of contrast and resolution of high-resolution digitizers[52-54] have demonstrated that currently available digitizers are approaching the resolution of film.

Our present experimental set up at The University of Calgary consists of an Eikonix 1412 digitizing camera capable of digitizing films up to 4,096 × 4,096 × 12 bits, a Megascan FDP-2111 frame buffer with a capacity of 4,096 × 4,096 × 12 bits, and a Megascan UHR-2008 high-resolution display monitor with a 2,560 × 2,048 × 8-bit display. Our experiments using a standard gray scale film strip indicated that after correcting for light intensity variations of the Gordon Instruments Plannar 1417 light box used to illuminate the films, and allowing for noise from all sources, the digitization can be considered useful up to 10 bits.[55] With a T-1 satellite channel (1.544 Mbps digital channel, sometimes referred to as DS-1 channel to distinguish from the analog channels using PCM transmission with analog-to-digital and digital-to-analog conversion), transmission of a 4,096 × 4,096 × 10-bit image takes about 2 minutes of the satellite channel time.[56] The actual transmission times must address the 540-ms satellite response time, and will depend on the protocol used for communication. Tests are underway for determination of the turnaround times for transmission and reception of images using satellite channel simulators. The image data are formatted using the ACR-NEMA message format.[49,57,58]

Clearly, with the advent of digitizers capable of 4,096 × 4,096 pixels with 4,096 shades of gray, digital teleradiology is ready to serve as an alternative to transporting patients or films and for securing reliable diagnoses by radiologists to patients in remote areas. However, the large amount of data involved in high-resolution images has created archival and data transmission problems. Commercially available systems address the problem of transmission to some extent, but the archival of data would still remain a problem. Data compression can bring down the amount of data and have a significant impact on the future development of teleradiology and related technologies in the 1990s.

IMAGE DATA COMPRESSION

Recently, there has been considerable research activity in reversible compression of medical images.[3,59-64] The requirement of high resolution in teleradiology resulting in enormous amounts of data, coupled with the fact that no loss of fidelity can be tolerated in compression and decompression in most medical applications, has motivated this interest. To capture all the diagnostic information in a chest radiograph or a mammogram, resolution of the order of 4,096 × 4,096 pixels with 10 to 12 bits/pixel is required.[45] Transmission of such large amounts of data over ordinary telephone lines results in large delays.[2] Although the use of high-data-rate satellite channels can alleviate the problem of transmission to some extent,[10] with the anticipated widespread acceptance of high-resolution teleradiology systems in the foreseeable future, archival of the image data would still remain a problem. Data compression schemes can bring down the amount of data handled and can have a great economic impact on teleradiology systems.

Natural images have a high degree of redundancy due to the correlation of pixels with their surrounding pixels. Further, the pixel values are not uniformly distributed over the range of values possible. Information theory[65-67] provides a basis for reducing redundancy, thereby achieving data compression. Accordingly, image data compression consists of two functions: decorrelation and encoding. Practical compression techniques combine decorrelation and coding in different ways. Further, in the case of some compression techniques, it may not be possible to perfectly reproduce the original image from the compressed one. Such compression techniques are said to be information lossy or irreversible. In contrast, the techniques in which the original image can be completely reproduced are said to be information preserving or reversible.

Image data compression has been investigated since the early 1970s[68-73] with various applications such as television, teleconferencing, and satellite imaging. With the advent of digital imaging modalities, interest in image compression in medical imaging gained momentum.[74] In most medical applications, no loss of information can be tolerated in compression and decompression of images. Some of the early studies involved direct application of existing image compression techniques and investigation of their suitability for medical images. Attempts have been made to quantify diagnostic information lost in compression and decompression.[60] Techniques drawn from progressive image transmission, where a poor-quality image is first transmitted at very low data rates and the quality is progressively improved with additional transmission of data, have also been investigated[61,75-77] for reversible data compression. Recently, Roos et al[59] made a comparison of various data compression techniques for medical images. They computed the entropy of images after application of a number of data compression techniques. However, they did not perform actual compression and decompression of images.

We have implemented a number of reversible image compression techniques for a proposed high-resolution digital teleradiology system.[11,55,78,79] The techniques implemented are straight Huffman coding,[80] Lempel-Ziv coding,[81-83] two-dimensional linear predictive coding,[72,78,84] transform coding using the discrete Fourier-, discrete cosine-, and discrete Walsh transforms,[85,86] linear interpolative coding,[59] and combinations thereof. Compression and decompression using these techniques have been implemented and tested on some mammograms and chest radiographs digitized to about 4,000 × 4,000 × 10-bit pixels.[11] We have achieved compression from 10 bits to 2.5 to 3.0 bits per pixel on these images without any loss of information. Some of these coding techniques, namely, linear predictive coding and transform coding, can result in higher compression when some errors in reconstruction are allowed.[11] Some of the techniques, namely transform coding and linear interpolative coding, can be adapted for progressive transmission of images.[11,61,75-77] These are potential requirements in a high-resolution teleradiology system. A practical teleradiology terminal would have all these techniques at its disposal for requirement-specific application.

Medical images such as mammograms, and radiographs of the chest and head commonly have large regions surrounding the central image that do not carry significant diagnostic information. Some relatively simple techniques that require operator intervention for eliminating such regions from coding are the use of binary masks,[12] and the use of predefined boundaries at a certain scale of digitization.[13] Moreover, in some applications, diagnostic information may be confined to certain features of the image. For example, in the case of chest radiographs for detecting pulmonary nodules, only the lung tissue may be of interest; the ribs and pulmonary vessels constitute "subject noise" and do not carry significant diagnostic information.[27] Scene analysis techniques[14,15,87] can be used to model such images for data compression. The idea of using pattern recognition methods in image coding is not new. As early as in 1971, Berger[67] pointed out that the field of rate distortion theory, in its broadest sense, encompassed the field of pattern recognition. However, practical coding methods based on scene analysis are relatively new. Forchheimer and Kronader[14] gave an excellent review of the current state of the art in pattern recognition–based image coding. One such method considers modeling the scene as a collection of three-dimensional objects against a background, and coding each object and background region separately. The decoder synthesizes the objects from a priori descriptions. These techniques of coding are called analysis-synthesis methods.[87] Such techniques have been used with a fair degree of success for modeling the three-dimensional structure of human faces by Platt and Badler,[88] and by Parke.[89] Welsh[90] used such a model for video telephone image compression, and coded the incremental changes in facial expressions and positions as changes in object orientation. Gray scale images can be modeled as random geometric models on a three-dimensional surface using fractals.[91,92] Fractals have been used for scene analysis and coding of gross features of scenes, achieving large compression ratios.[93-95] In the context of preserving the quality of medical images in encoding, scene analysis techniques can be used to automatically extract the regions of diagnostic interest and eliminate the background regions. Raghavan et al[12] used binary masks for eliminating the background regions of magnetic resonance images. These masks were manually generated and had to be redefined for each image. Lo and Huang[13] used predefined boundaries for eliminating regions of no diagnostic interest. These boundaries were defined for images taken by positioning the object at a particular viewing position of the digitizing camera. The concept of region/scene analysis for automatic elimination of the background in medical image coding is largely unexplored. We propose to look into region growing,[96] scene analysis,[97] and object modeling methods[98] for extracting regions of diagnostic interest from medical images for subsequent coding using adaptive predictive coding techniques. We foresee that integrated image analysis and compression systems would be at the heart of future teleradiology terminals.

The introduction of compression and decompression in teleradiology systems raises the question of overall throughput of the system in transmission and reception, and in storage and retrieval of image data. In general, the available channel capacity is increasing at a much slower rate than the availability of high-speed computational hardware. Thus, it would be economically viable to incorporate necessary computational hardware at transmission/storage and reception/retrieval ends for compression and decompression of images. However, compression of image data removes the inherent redundancy in images, thus making the data more sensitive to errors.[99] In dedicated communication links, appropriate error control should be provided for detecting and correcting these errors. In the case of packet-switched communication links, removal of redundancy by data compression would result in increased retransmission overhead. However, with modern digital communication links operating at typical bit error rates of 1 in 10^9, and channel utilization (throughput) efficiency of around 97% using modern high-level, packet-switched protocols,[100] the advantages of data compression far outweigh the overheads mentioned.

DISCUSSION

Teleradiology has come a long way from analog transmission systems using slow-scan television over standard telephone lines, to present-day, commercially available, microcomputer-based, low-resolution teleradiology systems. Some of the commercially available digital teleradiology systems are approaching the resolution requirements of high-resolution teleradiology as a feasible alternative to transportation of films/patients from remote areas to centers with better diagnostic facilities. The availability of high-resolution digitizers, display units, and digital hard copiers has made high-resolution digital teleradiology a feasible concept. However, the immense amount of data involved in the images will give rise to problems of transmission and storage. Data compression can bring down the amount of data involved in the transmission and storage of images generated at the remote sites and have a significant impact on the economics of the next generation of teleradiology systems. Commercially available systems have addressed the problem of transmission of data, but appear to have grossly ignored the potential of data compression techniques, optimized for medical images, to affect the economics of future teleradiology systems. We have developed a number of compression techniques for reversible compression of medical images. Our experiments with these compression techniques have shown that compression of the order of 4:1 is possible for a class of high-resolution medical images. Use of pattern recognition techniques offers a significant potential to improve compression even further. We plan to use these techniques in the prototype teleradiology system being developed at The University of Calgary.

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