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Design of an Emergency Teleradiology System Based on Progressive Transmission

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In clinical surgery, there are frequent needs for communication between the house staff and the attending physician in an emergency situation. To overcome the limitation of voice communication through the telephone line, we have designed an 'emergency teleradiology system' which can be used for emergency surgical and medical decision making.

This system can transmit the high quality images of CT, MRI, and other X-ray data using a PC attached to a modem through the conventional telephone line. It is based on the progressive transmission system which enables the successive update of a received image. The iterative residual coding/decoding algorithm efficiently compresses the image to maximally utilize the low bandwidth PSTN channels. This system also satisfies design requirements such as low-cost, ease of operation, fast transmission, and interactive image communication including voice.

Test results using several CT, MR, and X-ray images evaluate the compression performance, image quality, transmission time and computational time of the coding and decoding processes, thus demonstrate the usefulness of this system in an emergency situation.

Key Words: Emergency teleradiology, PSTN, progressive transmission, iterative residual coding algorithm

Teleradiology systems can be thought of as a unique combination of communication and computer technologies. They use electronic storage, transmission, and compression, to provide image access from remote sites. Various teleradiology systems (David and John, 1993; Rodney *et al.* 1993; Lyche *et al.* 1994) have been proposed as essential tools, which can help automating and expediting image transfer as needed for remote diagnosis of radiologic images. Unlike PACS (Picture Archiving and Communication System) systems (Chan and Ricky, 1991), teleradiology systems are typically specialized and designed for a specific purpose at a specific site. There have been few attempts (Kim *et al.* 1991; Choi *et al.* 1992) to implement this teleradiology system for rural health care support in Korea. The large volume of image data becomes limiting factor in system performance for the lack of wide band transmission media. Wide acceptance of a teleradiology system can be affected by over all system costs and the availability of communication media. (Whitman *et al.* 1994) Moreover, a teleradiology system must be designed to satisfy high speed image transmission as well as acceptable image quality (Leckie *et al.* 1993).

The aim of our system is not the diagnosis of radiological images but the support of medical and surgical decision making by the house staff in an emergent situation. In an emergency situation, particularly off hours, there are

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frequent needs for urgent communication between the house staff and attending physicians. The traditional method of telephone voice communication is not sufficient enough to precisely describe the patient's status, which results in misjudgment. In order to ameliorate such situation, an emergency teleradiology system for transmitting radiological images such as CT, MR, and X-ray data, has been designed.

MATERIALS AND METHODS

The implementing strategies are classified into two parts: hardware and software. In these two sub-sections, we refer to the cost-effectiveness and the modularity of this system. Finally, we show the technical methodology to achieve convenient user interfaces and the fast decision making by a suitable image compression algorithm.

System hardware

A teleradiology system is composed of image acquistion, storage, data transmission and a receiving device as shown in Fig. 1.

At the transmitter end, the hardware system is composed of a scanner capable of digitizing films, a display monitor with a 1024 ×768 resolution, and a 9600 bps (bits per second) external modem. The transmission machine is IBM compatible PC (486 DX2-50), which is connected to all of these peripheral devices.

At the receiver end, there may be an IBM compatible PC (386 or higher version) or notebook computer (COMPAQ 486) with the same kind of monitor and modem as the transmitter.

The external modem attached to the transmitting and receiving machine should support the V.42 standard protocol (William, 1995) to correct transmission errors. This modem can transmit or receive data without errors by use of High-level Data Link Control (HDLC) protocol. The Frame Check Sequence (FCS) field in the HDLC frame is used for CRC (Cyclic Redundancy Check) error detection with a 16-bit or 32-bit. If an error in the data field is detected during transmission, the corrupted frame is requested to be re-sent by the receiver. This eliminates the need to consider any

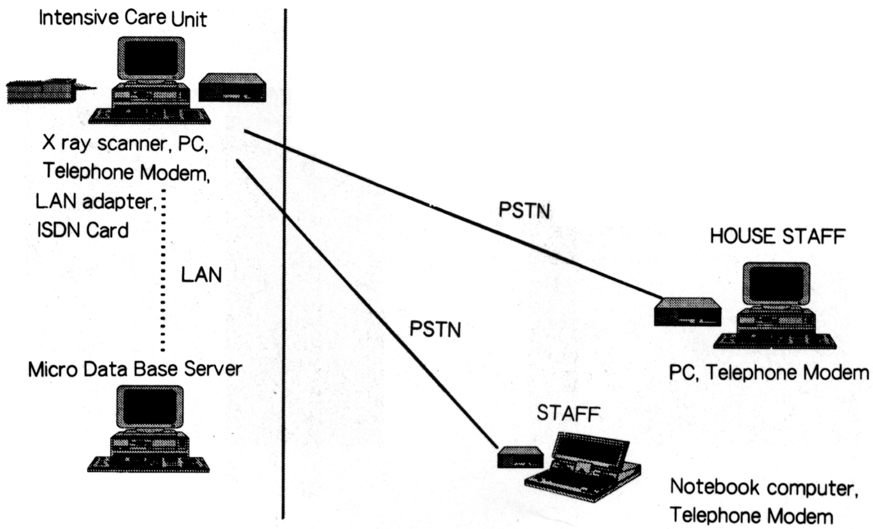


Fig. 1. *Teleradiology system.*
Teleradiology system is composed of image acquisition, storage, data transmission and receiving device.

type of higher level protocol for error detection in the software part of our system.

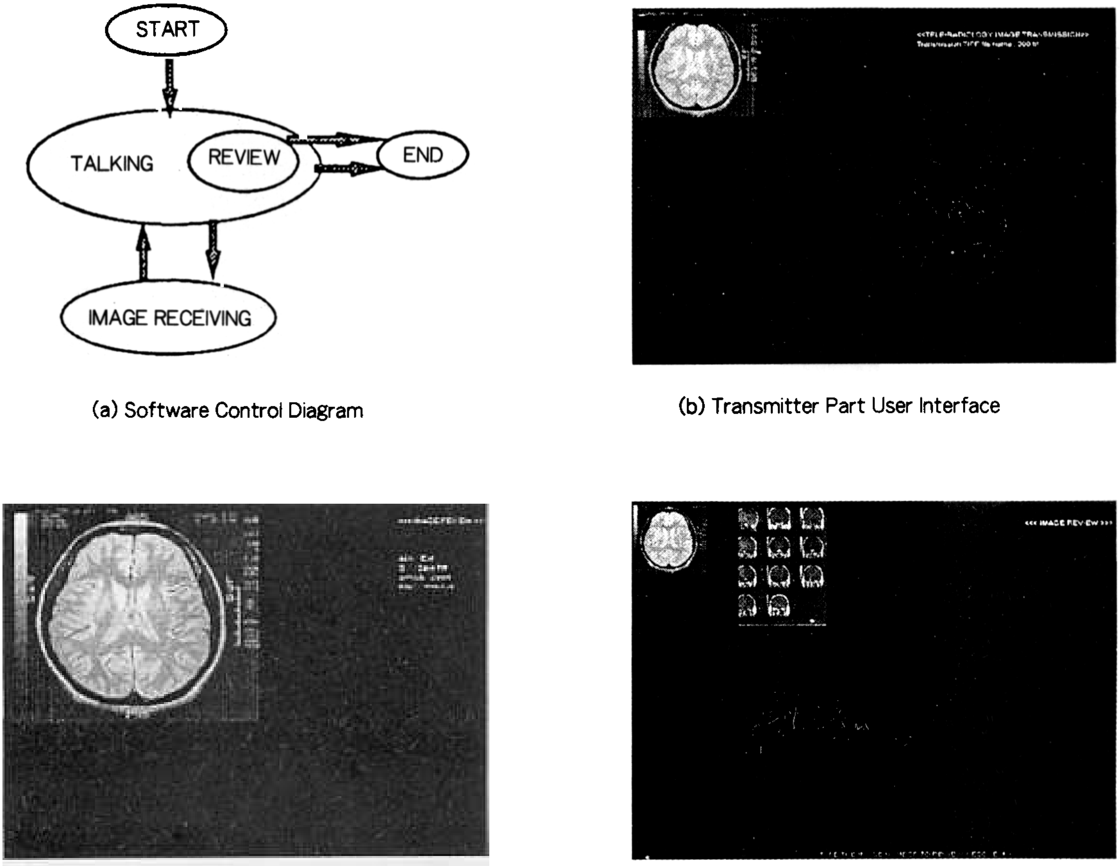
Finally, PSTN is adopted as a communication medium in this system because it is widely used in Korea and its operation cost is reasonable.

System software

The software of this system is composed of two parts: user interface and image compression. To achieve a user convenient environment, the user interface is designed with a simple menu and few key inputs. This reduces the amount of time invested to learn the software operations. To expedite the decision-making of the house staff, DCT (Discrete Cosine Transform) based iterative residual coding method is proposed in this system and the data are progressively transmitted. Details of each part are as follows.

User interface

In our system, user's key inputs are less than 5 keys. This program is devised to support toggling between data transfer and talking as in Fig. 2. Thus, if there is a need to receive or transmit an image after some discussion over the telephone, the user only needs



(a) Software Control Diagram

(b) Transmitter Part User Interface

(c) Receiver Part User Interface

(d) Review Mode User Interface

Fig. 2. *Software Control Diagram and User Interface of the System.*
In our system, user's key inputs are less than 5 keys, and this software is devised to support toggling between the data transfer mode (review mode) and the talking mode.

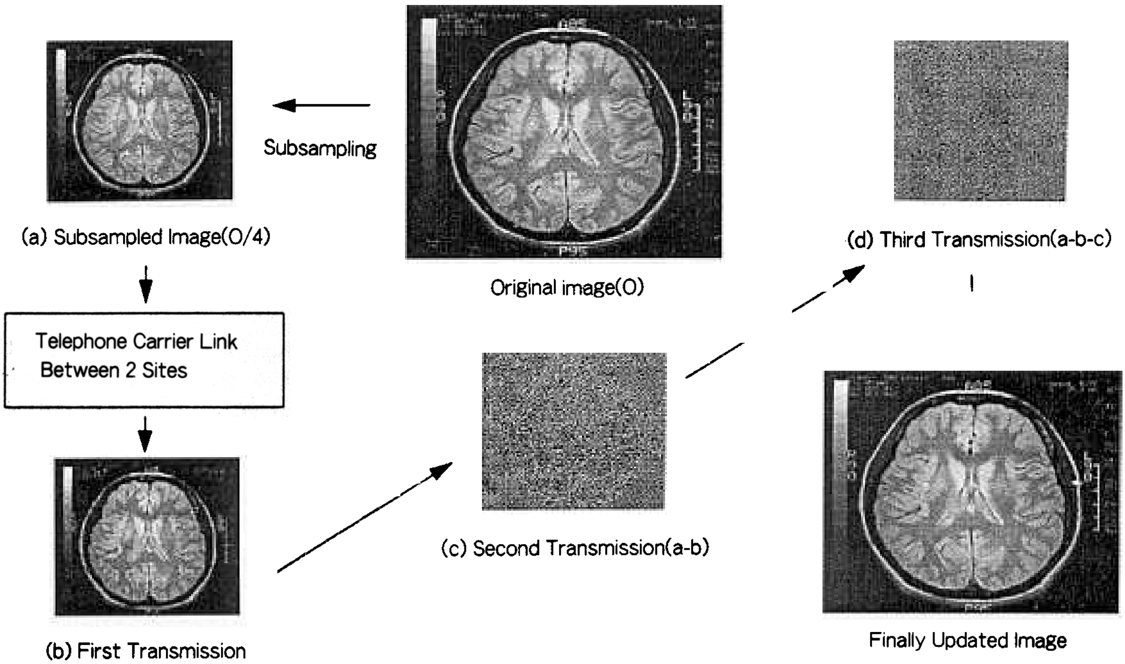


Fig. 3. *Image Coding Procedure of the System.*
Our coding scheme began with subsampling the original image by a factor of two to each horizontal and vertical direction, respectively. This subsampled version of the image was encoded and transmitted and then, in the next two stages of iteration, residual error images were obtained and compressed. Finally, from the interpolated version of the reconstructed image, the final residual error image was derived, and compressed very accurately.

to press a key. In addition, our system can review some images previously received. The review menu supports image zooming and saving.

Image compression

Because the PSTN, which gives the low bandwidth channels, seems to be unsatisfactory in transmitting large volume of image data, an efficient image compression scheme is the most important condition. To maximally utilize the low bandwidth capacity of PSTN, iterative residual coding technique using DCT (see APPENDIX) is carefully implemented. This compression technique includes the notion of progressive transmission that transmits the image data in stages. The reconstructed image progressively improves as more image data are received. Our coding scheme is shown in Fig. 3 and summarized as follows.

It begins with subsampling the original image by a factor of two to each horizontal and vertical direction, respectively. This subsampled version of the image is compressed through DCT, a quantization and an entropy coding step (see APPENDIX), and then transmitted. In the next two stages of iteration, residual error image (difference image between original and reconstructed image) is obtained and compressed by the use of a different quantization table. Finally, the interpolated version of the reconstructed image, which is of the same spatial resolution as the original image, is obtained. From it, the residual error image is derived and the fine quantization table with the smallest quantization step size is applied to obtain a good quality of the final reconstructed image.

RESULTS

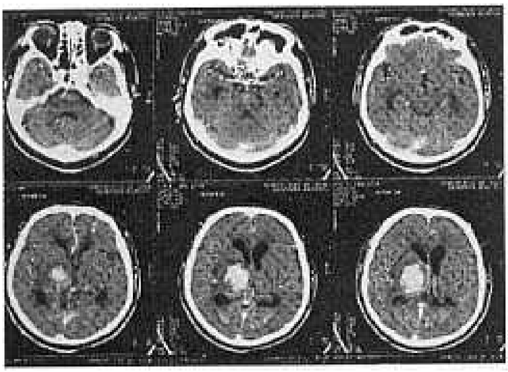
Most important factor affecting the success of the development of this system is how easily doctors can use this system in clinical practice. Most of the doctors who will use this system are not the experts in computer systems and usually only use the word processors and database applications. The test bed of this system was installed between the emergency room of Severance Hospital and the houses of several doctors who handle most cases of surgical emergency patients. The residents of neurosurgery and general surgery were assigned the transmitter. They received about 30 minutes training on this system. In most cases, there were no problems in transmission.

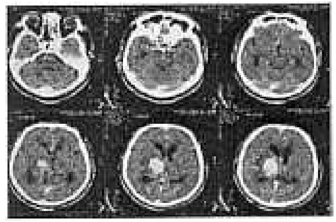
Fig. 4 is the actual example of the clinical application of this system. In this case, a patient arrived at the emergency room at midnight. The patient was semicomatose. He showed dense hemiplegia on the left side. The neurosurgery resident examined the patient and ordered a CT brain scan. The CT brain scan showed intracerebral hemorrhage on the thalamic area, so he called the oncall staff of neurosurgery to discuss the treatment plan of this patient. Before calling the oncall staff, he turned on the computer system and scanned the CT images with the scanner. It took about 3 minutes. After confirming the quality of scanned image, he called the oncall staff and described the patient's condition. During that time, the oncall staff prepared his home computer and the modem for data receiving, which took about 2 minutes. Then, the resident transmitted the first image. About six seconds later, the first low resolution image was received at the staff's computer terminal and the second, third, and fourth image were overlapped on the first image respectively.

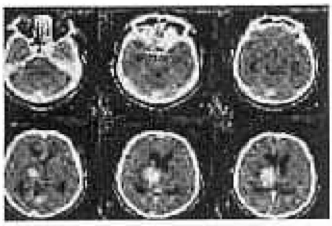
The system is devised such that during image reception, the oncall staff is able to review the received image with zooming function and usually recognizes the status of the patient with only the first two images. If he had any question about the patient, he can switch to verbal communication mode after receiving the complete one image. At this juncture, he can decide whether to receive another image or not. If not, he can just finish the data transmission and give direction of the treatment plan for the patient to his resident, such as preparing for surgery or other medical treatment. According to our tests, the entire procedure takes about ten minutes. Therefore, within 10 minutes, the resident can perform some urgent medical treatment as told from the oncall staff and waits for the oncall staff. It is quite reasonable to compare with the time delay taken by the oncall staff's moving from home to hospital and then making a decision.

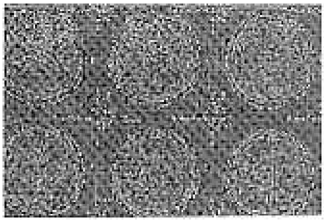
The technical performance of our system implemented in software using C language is evaluated. The 4 steps of iteration for the progressive image transmission scheme discussed in the previous section are tested by images using two MR (Magnetic Resonance), two CT (Computerized Tomography), and one X-ray films with 8 bits per sample to evaluate the compression performance, the reconstructed image quality, the transmission time, and the computational time of the coding/decoding process. The tests are performed with an IBM-PC compatible 486 personal computer with an externally connected 9600 bps modem. The reason why we choose the modem speed as 9600 bps is that a modem speed higher than 9600 bps may cause unstable transmission. [Hunter and Robinson, 1980; William, 1995] Thus, to overcome transmission instability, specific modem protocol such as Y-modem protocol or Z-modem protocol must be used for the transmission. However, the overhead of this kinds of modem protocol is very expensive, in the context of the emergency situation. Therefore, we conclude that the use of 9600 bps modem without any specific modem protocol is much more suitable for the optimization of this emergency system.

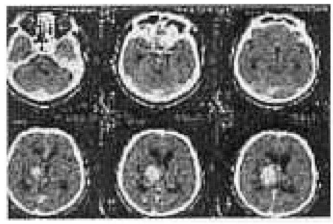
Columns 4 and 5 in Table 1 show the computational time of the encoding and decoding processes. The encoding (Te) and decoding (Td) time depends on the image size and the

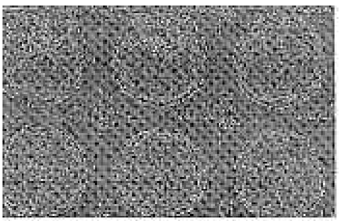

(a) Scanned CT Image

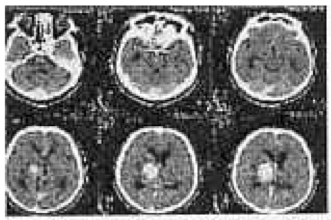

(b) Downsampled Image

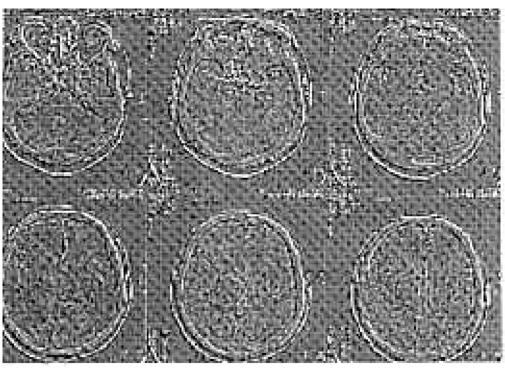

(c) First Transmission


(d) Second Transmission


(e) First Updated Image


(f) Third Transmission


(g) Second Updated Image


(h) Final Transmission

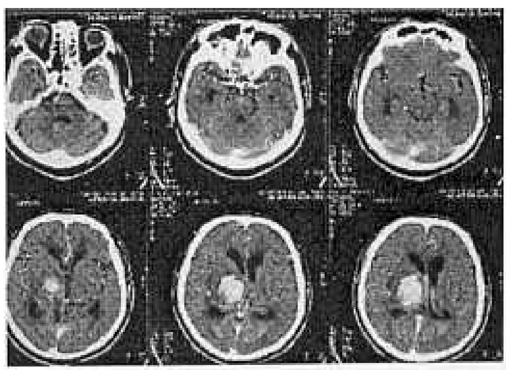

(i) Final Updated Image

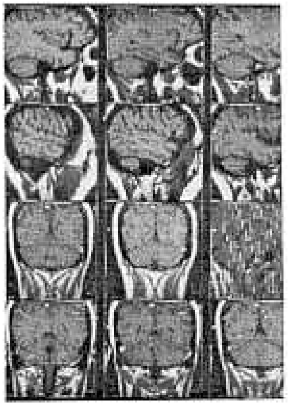
Fig. 4. *Real Application Example in I.C.U.*
On this case, the patient was arrived at the emergency room at midnight. Mental status of the patient was semicomatous. He showed dense hemiplegia on the left side. The brain CT scan of him showed intracerebral hemorrhage on the thalamic area.

compression ratio. They increase as the image size increases and as the compression ratio decreases. Compared to the transmission time (Tt), all of the required time of Te and Td are less than Tt. This results in the real time processing of encoding and decoding system with software.

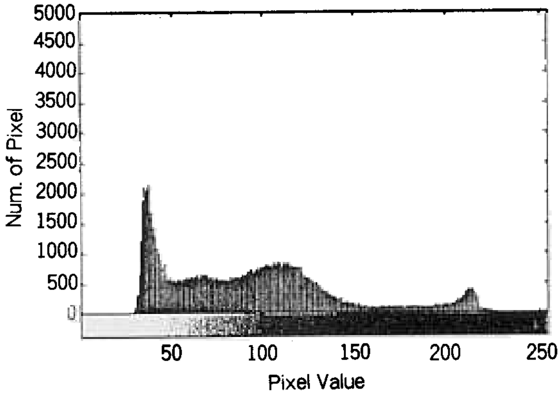
Column 6 in Table 1 shows the transmission time (Td) for each step of iteration. The image size and compression ratio also affect Td. The first transmission takes 2 to 6.6 sec and the total time required for 3 stages of iteration ranges from 5.1 to 23.2 sec. Although the transmission time depends on the image resolution, these results show that the first image will be displayed on the monitor within 6.6 sec and sequentially updating the image through three stages of transmission is satisfactory for emergency medical and surgical decision-making in all 5 testing cases. The usefulness of the emergency teleradiology system strongly depends on how quickly one can recognize the image. The 4th iteration takes the longest time (26.5~83.8 sec). However, it will not pose a problem because the final image with fine resolution will be updated when the clinician reviews the received image.

Table 1. Results of a 4-step progressive image transmission scheme using 2 MR, 2 CT, and 1X-ray images

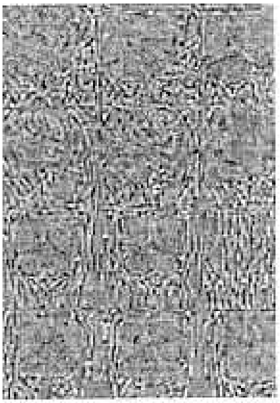
Image	Image size (dytes)	Iteration No.	Encoding Time: Te (sec)	Decoding Time: Td (sec)	Transmission Time: Tt(sec)	Compression ration	MSE
MR1	61,248	1	1	0	2.0	32.0	12.8
	61,248	2	1	0	2.4	25.9	9.8
	61,248	3	2	1	2.7	23.5	8.7
	244,992	4	2	2	26.5	4.7	4.0
		(Total)	6	3	33.6	7.5	
MR2	156,672	1	2	1	6.6	48.7	15.4
	156,672	2	3	1	7.9	40.6	11.9
	156,672	3	5	1	8.7	36.6	10.3
	626,688	4	6	5	83.8	3.8	4.9
		(Total)	16	8	107.0	5.7	
CT1	59,200	1	1	0	4.0	15.3	26.3
	59,200	2	1	0	4.3	14.3	22.3
	59,200	3	2	1	5.1	12.2	20.0
	236,800	4	3	3	51.4	2.4	9.7
		(Total)	7	4	64.8	3.8	
CT2	59,200	1	1	0	3.1	20.2	20.0
	59,200	2	1	0	3.8	16.4	16.0
	59,200	3	2	1	4.1	15.1	14.3
	236,800	4	3	3	39.9	3.1	6.7
		(Total)	7	4	50.9	4.8	
X-ray	62,400	1	1	0	3.1	58.5	6.9
	62,400	2	1	0	3.8	46.0	4.8
	62,400	3	2	1	4.1	41.5	4.1
	249,600	4	2	2	39.9	11.1	2.0
		(Total)	6	3	50.9	16.4	



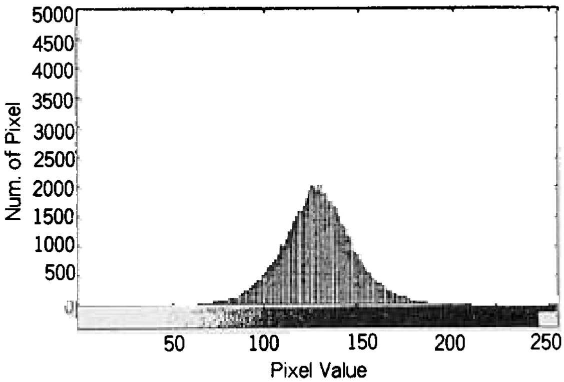
(a) 1st Coding



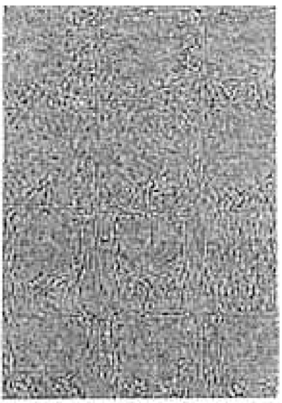
(b) Histogram of (a)



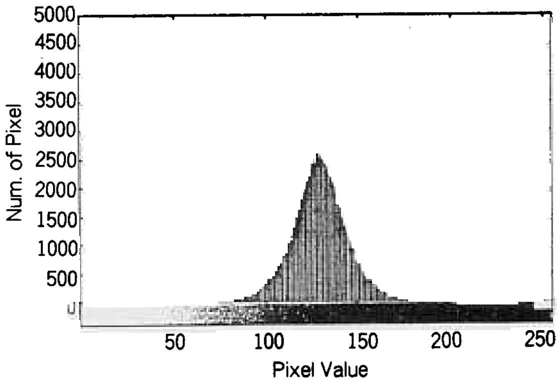
(c) 2nd Coding



(d) Histogram of (c)

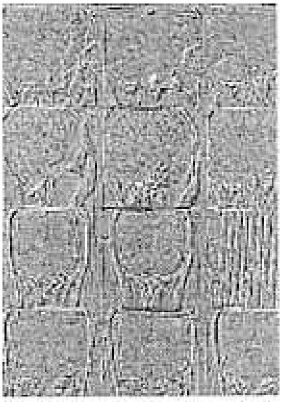


(e) 3rd Coding

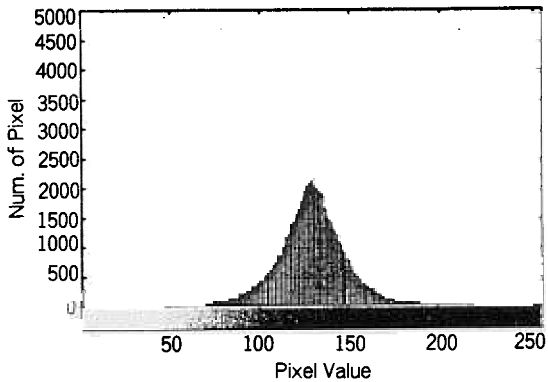


(f) Histogram of (e)

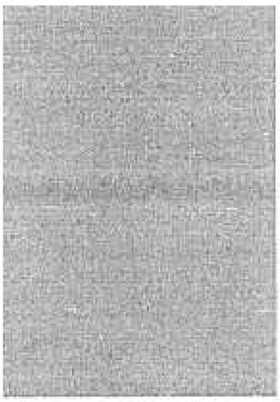
Fig. 5. *Images at each stage and their histograms.*
The original histogram shows the wide range of distribution of each gray level. In contrast, the reconstruction error variances tend to be a small value as the number of iterative stages increase.



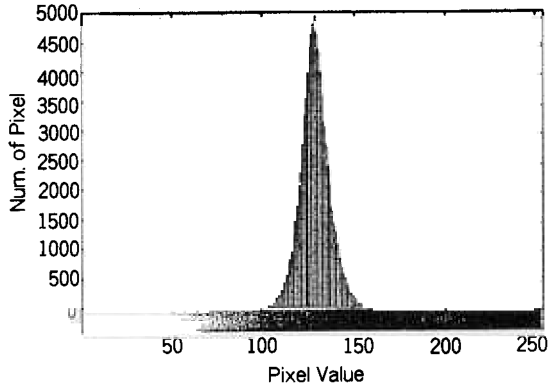
(g) Final Coding



(h) Histogram of (g)



(i) Final Error



(j) Histogram of (i)

Fig. 5. Continued.

The compression ratio (CR) which is an index that shows the amount of compression achieved by a coding algorithm, is shown in column 7 of Table 1. The CR is defined by the ratio of the total number of bytes in the original image divided by the total number of bytes in the compressed image:

$$\text{compression ratio} = \frac{\text{Total number of bytes in the original image}}{\text{Total number of bytes in the compressed image}} \quad (1)$$

Higher CRs result in greater compression. Therefore, the size of the compressed image and the transmission time will be smaller. If the iteration increases, the reduction of the quantization step size results in a decrease of the compression ratio, which means the finer resolution images will be updated. CT images achieve less CRs than MRs. X-ray images achieve the highest CR of all images. MR and CT images with multiple slices are more complex than a plain chest X-ray; also, MR shows a clearer view than CT because the spatial redundancies of MR, CT, and X-ray image are different from each other, and thus will affect the CRs.

The coding algorithm in progressive transmission scheme is lossy, so some errors in the reconstructed images can be tolerated. In this case, the mean squared error (MSE) was used as a measure of system quality. If the input and reconstructed images consist of N×N array of pixels f(x, y) and g(x, y), x, y = 0, 1, ..., N-1, then the error between an input pixel and the corresponding reconstruction pixel is defined by

$$MSE=\sqrt{(g(x, y)-f(x, y))^2} \quad (2)$$

The MSE depends on the compression ratio. That is, low MSE value means that there are great details in the reconstruction image and thus the CR can't be high. It is seen from columns 8 and 9 in Table 1 that increasing the iteration can provide a lower MSE. This also indicates that the reconstruction image quality improves significantly with the use of progressive update sequences.

Fig. 5 shows the histogram of the original and the first, second, third, and fourth transmitted images. The original histogram shows a wide range of distribution of each gray level. In contrast, the reconstruction error variances tend to have a smaller value as the number of iterative stages increases. As the data of the fourth image are concentrated around the center value, it is clear that the best image quality and coding performance may be achieved from the final updated image. In terms of coding efficiency, the smaller the variance, lower bits will be allocated for a given quality and a higher quality of reconstruction image will be obtained for a given compression ratio. Therefore, the elements of the residual error image tend to become more decorrelated, since each iterative stage partially removes the statistical redundancy of the original image.

DISCUSSION

Telemedicine systems are being developed and implemented around the world. Three major application fields of this system are teleradiology (David and John, 1993; Rodney *et al.* 1993), telepathology (Yu *et al.* 1994), and teleconsultaion (Jagdish, 1989). With the advance of optical fiber and digital switching techniques, there has been a tendency to utilize the higher bandwidth to obtain the diagnostic image quality of higher resolution and fast transmission. However, the communication system is very expensive, which has limited this approach to the military use and the national demonstration program. (David *et al.* 1993; Lyche *et al.* 1994) In contrast, our system is designed to maximally utilize the currently available lower bandwidth channels such as PSTN. This is because the successful use of teleradiology is a function of the convergence of several economic and technological factors (Gernish and Bartsch, 1993). Our approach gives the insight to use the telecommunication technology as a medium which allows the decision-making in an emergency situation where the referring clinicians are located at some distance from the hospital.

The first step in the operation of the emergency teleradiology system is data acquisition. An ideal configuration of the data acquisition process is direct connection to the imaging modalities such as CT, MR and X-ray through the DICOM 3.0 (Digital Imaging and Communication standard) interface (Moore *et al.* 1994). Although multi-vendors offer this interface, its cost is too high and old equipment cannot support it. In an emergency situation, many radiological films are generally transferred to the emergency center from the primary care unit. Therefore, in the initial phase of installation, the images are acquired through the commercially available film scanner (Hewlett Packard Scanjet IIcx) under WINDOWS (Microsoft Windows 3.1) environment. Multiple scanned images are subjectively tested by the use of pair-comparison methods (Gonzalez and Woods, 1992). It concluded that the scanned quality of a plain X-ray image will not be sufficient enough to diagnose due to artifact, but the quality of digital images, such as CT and MR, will be sufficient for the purpose of decision making.

Many developers (Fuhrman *et al.* 1993; Leckie *et al.* 1993) said that the usefulness of emergency teleradiology system strongly depends on the speed of image transmission in the case of an emergency situation. In our system, after connecting the call by dialing, the total time spent before the first actual image transmission encompasses the computer operation and carrier link time. The average 3 minutes of initial computer and scanner operations, and 15 seconds of carrier link time are generally required.

After completing the carrier link, the transmission time mainly relies on the size of compressed bit stream. In the experimental situation, the average time of 6, 6, 7, and 60 seconds are spent regarding each of the 1st, 2nd, 3rd, and 4th images with 14"×17" size, respectively. As Stephan *et al.* (1995) mentioned, the progressive update sequence gives the additional benefit that the referring clinician can not recognize the time spent due to low bandwidth transmission.

Leckie *et al.* (1993) points out that the ultimate success of teleradiology system depends on the acceptance by the end users-clinicians. The advantages of our teleradiology system are easy manipulation of the system and rapid image transmission. To operate the system quickly and reliably in an emergency situation, only 5 keys with minimum functions are used. It minimizes the mis-operation of a non-computer oriented user. A specially designed video display program, which is optimized by C language, enables the display of a 1024×768 image resolution within 0.5 second. To make the surgical and medical decision, voice communication is important during the image transmission. But, it is not possible to transmit the voice and images simultaneously on the PSTN. The Remote Consultations and Diagnosis (RCD) system designed by Martinez *et al.* (1995) in the global PACS environment uses a separate telephone line for voice communication during the session as required. The advantage of our system is the use of one telephone line which use the time multiplexing method. The precise control of MODEM changes its status to either data or voice mode if the voice communication is necessary between sender and receiver.

Almost all of the teleradiology systems developed so far are used for diagnosis by remote radiologists who are experts or as a part of full PACS. Thus, lossless compression techniques (Stephan *et al.* 1995), such as arithmetic coding, DPCM, HINT, *etc,* are widely applied since the images are fully recoverable. Lossless algorithms typically yield compression ratios of 2: 1; such a low rate of compression would not make a significant impact on the system since there would still be a long wait for image transfers. Lossy compression techniques providing the variable compression ratio could be incorporated into the system. But they also have limitations, since they are not reversible. Our carefully designed residual coding algorithm refines its reconstruction image quality with the increasing number of iteration. Although the loss incurred from the low bit rate coding until the second stage results in artifacts and the blurring of important features, the third and fourth stages of refinement overcome the above drawbacks.

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APPENDIX: Image Compression by DCT

2-Dimensional DCT (Discrete Cosine Transform) is definded by

$$C(u,v)=\alpha(u)\alpha(v)\sum_{x=0}^{N-1}\sum_{y=0}^{N-1} f(x,y)\cos\left\{\frac{(2x+1)u\pi}{2N}\right\}\cos\left\{\frac{(2y+1)v\pi}{2N}\right\}$$

for u, v=0, 1, 2, 3, ⋯, N-1 (A-1)

$$f(x,y)=\sum_{u=0}^{N-1}\sum_{v=0}^{N-1} \alpha(u)\alpha(v)C(u,v)\cos\left\{\frac{(2x+1)u\pi}{2N}\right\}\cos\left\{\frac{(2y+1)v\pi}{2N}\right\}$$

for x, y=0, 1, 2, 3, ⋯, N-1 (A-2)

In both equations (A-1), (A-2), $\alpha(\cdot)$ is

$$\alpha(\cdot)=\begin{cases}\sqrt{\frac{1}{N}} & \text{for } u=0\\ \sqrt{\frac{2}{N}} & \text{for } u=1,2,\cdots,N-1\end{cases} \quad \text{(A-3)}$$

The three major stages of image compression consist of DCT, quantization and entropy coding. To reduce the computational burden, the image is generally partitioned into 8×8 (N=8) blocks and each block is independently transformed using the DCT. Because the transform coefficients are compacted into a minimum number of coefficients, they provide a suitable representation for efficient coding.

Quantization achieves compression by representing transformed coefficients with no greater precision than is necessary to achieve desired image quality. The transformed coefficients are quantized according to a variable length quantization table. Also, this variable length bits allocation, that is entropy coding, achieves additional compression by encoding the quantizied coefficients more compactly based on statistical model.