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PDA–Phone-Based Instant Transmission of Radiological Images over a CDMA Network by Combining the PACS Screen with a Bluetooth-Interfaced Local Wireless Link

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Remote teleconsultation by specialists is important for timely, correct, and specialized emergency surgical and medical decision making. In this paper, we designed a new personal digital assistant (PDA)–phone-based emergency teleradiology system by combining cellular communication with Bluetooth-interfaced local wireless links. The mobility and portability resulting from the use of PDAs and wireless communication can provide a more effective means of emergency teleconsultation without requiring the user to be limited to a fixed location. Moreover, it enables synchronized radiological image sharing between the attending physician in the emergency room and the remote specialist on picture archiving and communication system terminals without distorted image acquisition. To enable rapid and fine-quality radiological image transmission over a cellular network in a secure manner, progressive compression and security mechanisms have been incorporated. The proposed system is tested over a code division Multiple Access 1×-Evolution Data-Only network to evaluate the performance and to demonstrate the feasibility of this system in a real-world setting.

KEY WORDS: PDA, teleradiology, image transmission, Bluetooth, CDMA 1× EV-DO, WLAN

INTRODUCTION

In emergency situations (especially during off hours), there is a frequent need for urgent communication between medical specialists outside the hospital and the attending physicians in the emergency room. Remote consultation is important for timely, correct, and specialized emergency and surgical and medical decision making, which is critical in increasing patients' chances of survival and in preventing patients from suffering serious consequences. However, verbal communication through telephones alone is not sufficient to describe the patient status to remote specialists. Therefore, the transmission of radiological images can be useful to supplement the limitations of verbal communication. Recently, personal digital assistant (PDA) technology that has been incorporated into cellular phones (PDA phones) has attracted attention to emergency teleradiology systems due to its mobility and portability. Some PDA–phone-based systems use web technology to interface with picture archiving and communication systems (PACS) on which remote specialists navigate the menus to spot the radiological images relevant to each individual emer-

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gency patient.[1–4] Although high-speed mobile communication, such as 3G cellular networks, enables the rapid transmission of radiological images to the mobile device, it is sometimes insufficient for the remote specialist to find relevant images or to match the images seen with the correct emergency physician on duty in the emergency room (synchronization) through the multistep menu navigation. An alternative to this method is to photograph the PACS monitor using a digital camera, which allows the user to bypass the menu navigation system.[5,6] Because most PDA phones have a built-in digital camera, the use of a PDA phone can be convenient to perform both the photographing and transmitting processes and can also avoid a synchronization problem. However, some distortions occurring during the photographing process cannot be avoided.

In this paper, we designed a new PDA phone-based emergency teleradiology system (PET) system to overcome the above drawbacks. By combining PDA–phone-based cellular communication with Bluetooth-interfaced local wireless links, the PACS screen in an emergency room can be shared instantly between the remote specialist and the emergency physician on duty without distortion or image synchronization problems. Additionally, the progressive compression and security mechanisms are incorporated in the proposed system to gain an advantage over the limited bandwidth of the cellular network and also to prevent the possibility of patient data intrusion due to the air interface. The designed system was tested over a code division multiple access 1× evolution data only (CDMA 1× EV-DO) network to evaluate its performance and demonstrate its feasibility in a real-world setting.

MATERIALS AND METHODS

System Operation

The PET system was designed to instantly transmit radiological images from an attending emergency physician on duty in an emergency room to a specialist located outside the hospital for time-critical emergency consultations. Both physician and remote specialist are linked together by PDA phones through a CDMA cellular network to facilitate the consultation process during movement as shown in Fig. 1. Consultants can be at any place without being forced to stay at a fixed location such as their home or hospital, and they can even be moving. To eliminate the fixed location constraint for the attending physician, the PDA phone is equipped with a Bluetooth module that enables a wireless linkage between the PACS terminal and the attending physician within the emergency room. Therefore, the attending physicians are not forced to stay near the PACS terminal during consultation, so they can be near the patient instead.

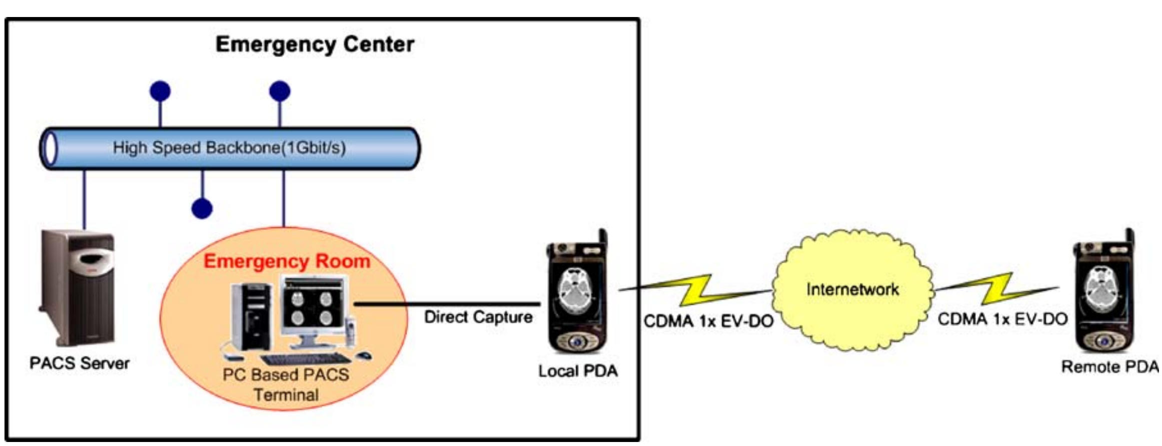

Fig 1. A system configuration of PDA–phone-based emergency teleradiology system. PACS should be installed in the emergency room. Bluetooth and cellular communication link the PACS screen to both attending physician's PDA and remote consultant's PDA.

The operation procedures are summarized as follows:

(1) The attending physician in an emergency room displayed relevant images to be consulted on the PACS terminal. Compared with PDA phones, which have limited resolution and user interface, a PACS terminal makes it easier for the user to find relevant images with a widely recognizable display size.
(2) When the attending physician initiated the image transmission to the consultant by the designated one-button click, the PACS terminal captured the screen as a digital image, compressed it in a multiresolution format, and then transmitted it to the attending physician's PDA phone using the Bluetooth interface.
(3) The attending physician's PDA phone relayed the compressed images received from the PACS terminal to the consultant's PDA phone through a CDMA network. Because the attending physician and the consultant are linked to the PACS terminals through air interfaces (Bluetooth and CDMA), the attending physician can move freely in the emergency room within the Bluetooth communication boundary, and the consultant can move freely to any place as long as an uncovered region of the CDMA communication is not encountered.

Specifically, dedicated routines residing within the PACS terminal as background programs were developed to directly capture the screen of the PACS terminal as an image file, to compress it as a multiresolution format, and to relay it to the attending physician's PDA phone. In addition, a PDA image viewer was also developed to allow image magnification and rotation; physicians can also zoom in and out and can rotate the image to supplement the limited screen resolution of PDA phones.

The operational conditions for PET systems are:

(1) PACS should be installed in the emergency room.
(2) The PACS terminal in the emergency room should have a Bluetooth module.
(3) The attending physician's PDA phone should have both Bluetooth and CDMA interfaces.
(4) The consultant's PDA phone should have a CDMA interface.

System Design

(a) Multiresolution Image Compression

The multiresolution format was chosen to compensate for the discrepancy of the screen resolutions between the PACS terminal and the PDA phone, as well as to maximize the transmission efficiency through successive updates of the received images. Because the personal computer (PC) is generally used as a PACS terminal in emergency rooms, the screen resolution of 1,280×1,024 pixels that is used with PCs is considered as the captured image resolution. The captured image is first subsampled as a factor of 4, which forms a subsampled image resolution of 320×256 pixels. This measurement approximately matches the PDA phone's screen resolution of 320×240 pixels. The upper 16 lines from 256 to 240 pixels are discarded to match the vertical resolution when displaying the received image on the PDA screen because the menu bar is generally occupied at the upper part of the screen. The progressive transmission was conducted by

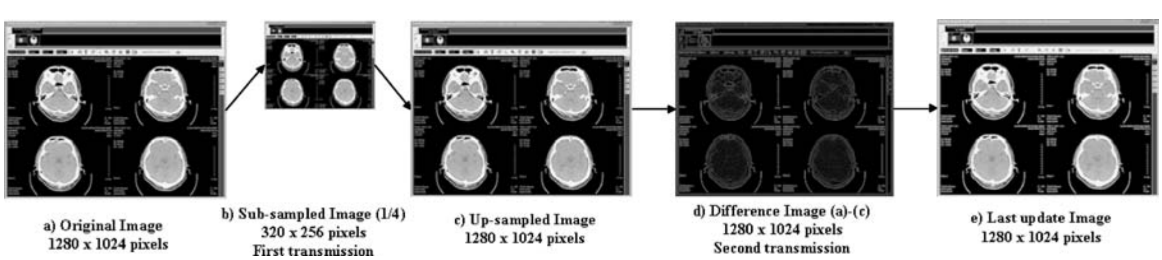

Fig 2. Multiresolution image compression by two-stage application of JPEG progressive compression. (a) Original image 1,280×1,024 pixels. (b) Subsampled image (1/4) 320×256 pixels, first transmission. (c) Upsampled image 1,290×1,024 pixels. (d) Difference image (a)–(c) 1,280×1,024 pixels, second transmission (see the expanded Fig. 2d). (e) Last updated image 1,280×1,024 pixels.

Fig 3. Secure wireless transmission of radiological image through Bluetooth with SAFER+ scheme and through CDMA 1×-EVDO with mobile VPN.

two-stage applications of Joint Photographic Experts Group (JPEG) progressive compression as shown in Fig. 2. The subsampled image is compressed through discrete cosine transform, quantization, and entropy coding to form the first compressed image to be transmitted.[7] Then, the first compressed image is decompressed and upsampled to match the captured image resolution of 1,280×1,024 pixels. Finally, the residual error image, which is formed by calculating the difference between the captured and the upsampled image, is compressed to form the second compressed image.

(b) Security

The vulnerability of data during transmission through an air interface can be reduced by incorporating secure transmission methods at each interface including Bluetooth and CDMA as shown in Fig. 3. When the images are relayed to the attending physician's PDA phone through the Bluetooth interface, a security mechanism is also conducted by the SAFER+ algorithm, which uses a 128-bit coding engine.[8] SAFER+ is a basic component in the Bluetooth authentication mechanism, and it is capable of validating each linked Bluetooth device with an encrypted personal identification number. Security over a CDMA cellular network (between the attending physician and the consultant) can be

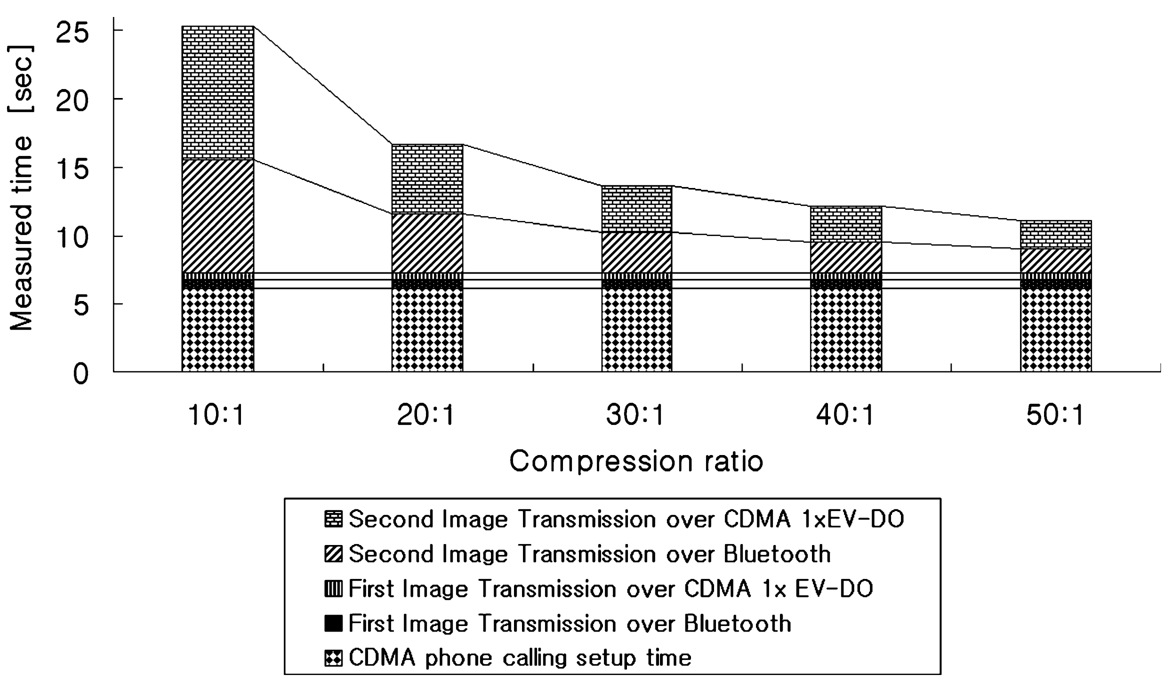

Fig 4. Transmission time in terms of compression ratio. Total transmission time is affected by CDMA phone-calling setup time, first image transmission over Bluetooth, first image transmission over CDMA 1×-EVDO, second image transmission over Bluetooth, and second image transmission over CDMA 1×-EVDO.

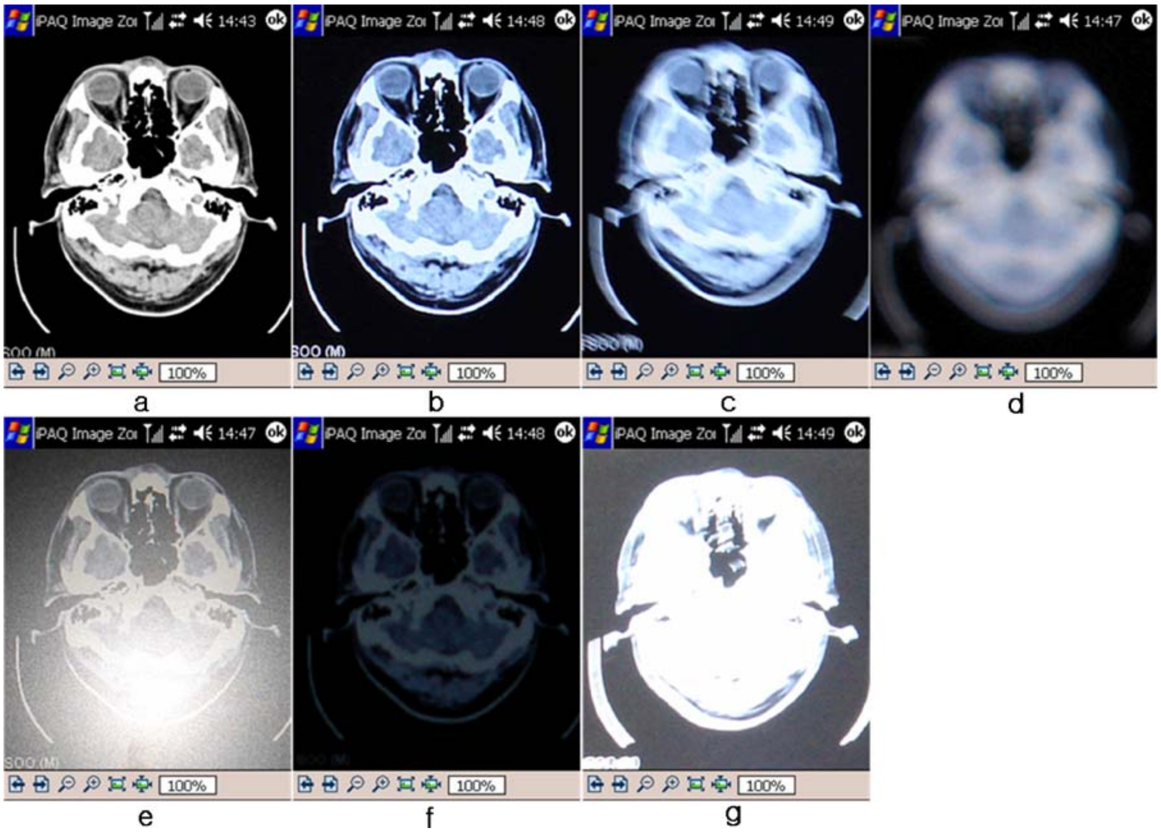

Fig 5. Regarding image distortion, the proposed system (b) is compared with the direct photographing method (c)–(g). (a) Original image. (b) Undistorted image acquisition. (c) Overexposed distortion. (d) Underexposed distortion. (e) Reflection distortion due to camera flash. (f) Camera-shaking distortion. (g) Unmatched camera focus distortion.

performed by using a mobile virtual private network (VPN). Mobile VPNs protect IP packets through IP Sec protocol and tunneling.[9]

Test System Configuration

Experimentation was performed between the Severance Hospital's Emergency Center (located in the center of Seoul) equipped with a PACS Server System (Centricity 2.0™, General Electronic Company, Milwaukee, WI, USA) with a 1-Gbit/s backbone communication network and a specialist (consultant) walking outside the hospital (approximately 20 km away). The PACS terminal systems (Pentium IV 2.6 GHz, 512 MB, 1,280×1,024 screen resolution, 17'-inch LCD monitor) are linked with a USB-typed Bluetooth communication adapter (ParaNee™, Handywave Co., Korea). The PDA phone device (HP iPAQ rw6100 PocketPC, Hewlett-Packard Co., Korea) was equipped with a Bluetooth communication module (Bluetooth SDIO Card™, Socket Communications Inc., USA) and a CDMA 1× EV-DO modem card (MSM™ 5500 CDMA 1× EV-DO Modem, Qualcomm, USA). The PDA phone used the Pocket PC 2003 Operating System. Images were displayed on the PDA phone, which had a 240×320-pixel TFT LCD (Thin Film Transistor Liquid Crystal Display) screen.

RESULTS

With respect to two-stage progressive transmission, the first image was formed from the subsampled image with a fixed compression ratio of 10, and the second (residual) image was

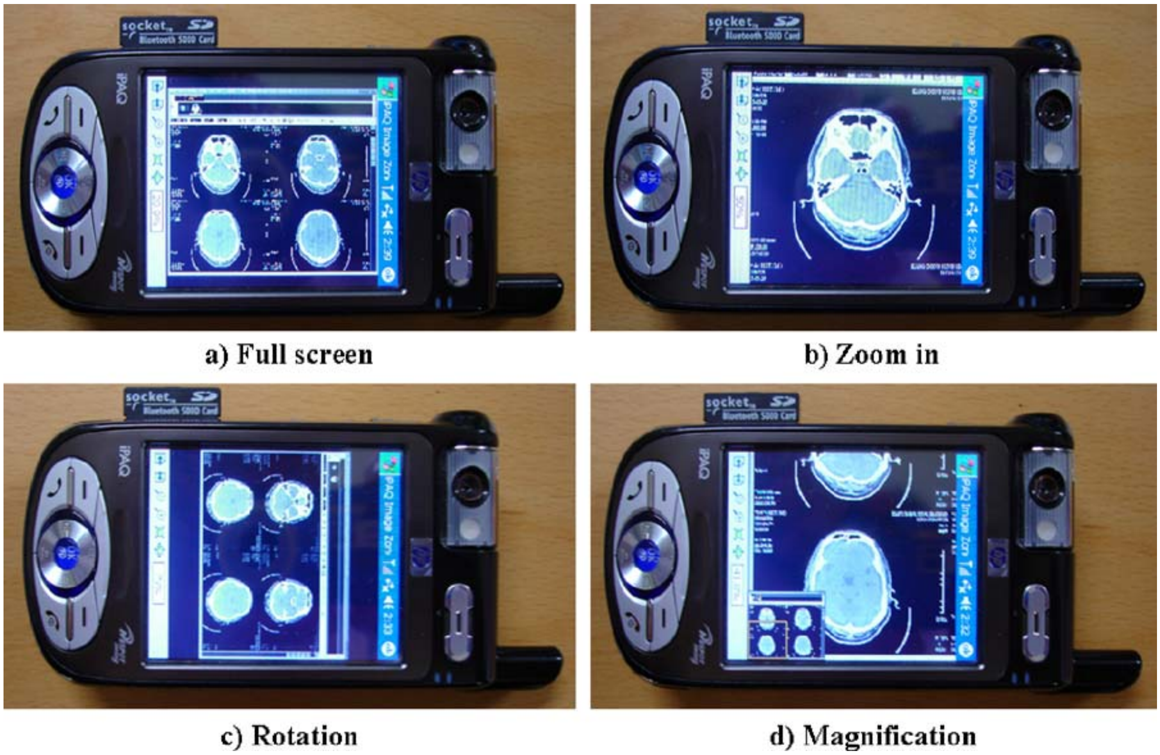

Fig 6. Image-viewing functions including (a) full-screen display, (b) zoomed display, (c) rotated display, and (d) magnified display are implemented to display with different resolution, display format, and orientation.

composed by applying different levels of compression ratios of 10, 20, 30, 40, and 50 to the residual images. The size of the first image was 8.1 KB. The sizes of the second images were 127.8, 65.6, 42.3, 33.6, and 26.4 KB, which, respectively, correspond to the compression factors of 10, 20, 30, 40, and 50. As shown in Fig. 4, the total transmission time decreases as the compression ratio increases (and the second image size decreases). That is, the transmission times over both Bluetooth and CDMA depend on the size of the second image. The measured mean CDMA phone-calling setup time and first image transmission times through the Bluetooth and CDMA networks with 30 time measurements were 6.1 s (standard deviation of 0.86), 0.6 s (standard deviation of 0.2), and 0.5 s (standard deviation of 0.06), respectively. Specifically, the phone-calling setup time was not affected by image sizes with respect to first and second images, and the first image transmission time was irrespective of the compression ratios applied to the second image since the fixed compression was used for the first image. Therefore, the total transmission time greatly depends on the compression ratio applied to the second image. Because a compression ratio of 10 is generally accepted as a radiographical-quality JPEG image without loss of diagnostic significance,[10] the total transmission time takes 25.3 s. Although the maximum allowable compression ratio of 30 (a loosely defined compression ratio without compromising diagnostic quality) is considered,[11] the image transmission can be performed within 13 s. Moreover, the improvement in terms of image transmission time was not significant for high compression ratios of 40 and 50. Nevertheless, the first image can be shown on the consultant's PDA within 7.2 s, which allows for fast emergency decision making. Because the resolution of the first image matches the maximum display resolution of the PDA phone, the fine resolution image (second image) is progressively updated at a background program behind the display screen while inspecting the image seen on the consultant's PDA phone. The fine resolution image of $1{,}280 \times 1{,}024$ pixels can be required but only after the consultant requests zooming and magnification to inspect the image in detail on the PDA phone's screen with a limited resolution of 320×240 pixels.

Because the amount of image distortion is one of the critical factors involved when conducting emergency consultations remotely, the PET system is compared with the direct photographing method shown in Fig. 5. The image distortion at the receiver's PDA phone can be caused by loss due to image compression and also by distorted image acquisition. When comparing the displayed image for the proposed PET (see Fig. 5b) to the original image (see Fig. 5 a), a significant difference between both images is not recognizable because the compression ratio of 10 did not produce any significant losses while the proposed PET is free of distorted image acquisition and while direct photographing method is subject to distorted image acquisition. By conducting exaggerated experimentation with the direct photographing method, diverse patterns of distortion including mismatched contrast settings with too-high contrast (see Fig. 5c) and too-low contrast (see Fig. 5d), reflections due to the camera flash (see Fig. 5 e), camera shaking (see Fig. 5 f), and unmatched camera focus (see Fig. 5g) were observed in contrast to the undistorted image acquisition (see Fig. 5b).

Finally, in terms of image manipulation functionalities, image-viewing functions (rotation, zoom in, and magnification) which have been developed to operate on a remote consultant's PDA phone as shown in Fig. 6 can be useful to inspect the received images with different resolutions, display formats, and orientations.

DISCUSSION

Both the timely and high-quality displays of radiological images are of utmost importance in a PDA–PET system for correct surgical and medical decision making from a remote location.

When accessing the images relevant to emergency patients for teleconsultation, the number of steps needed to navigate menus, the processing time for each menu, and the ease of menu operation are all related with the timeliness of image display. In the case of the web-based system interfacing with the PACS remotely, several steps of menu navigation are unavoidable, as are some menu's relationships to image data (requiring more access and display time than textual data). Therefore, the amount of time spent using menus related to image access and display and also the number of navigational steps should be minimized. They are more severe when using PDAs because PDAs have less memory and processing power than PCs and because menu operations in PDAs on the small display panel using a stylus pen are more time consuming than menu operations in the PC. Nevertheless, the advantage of the PDA over the PC is obvious because of its mobility and portability. If the menu navigation is performed on a PC (PACS terminal) instead of a PDA, the PC screen is digitally captured, the captured image is transmitted to the remote specialist, and the received image is displayed on the PDA, then several steps of menu navigation on the PDA can be omitted. Transmitting images using a PDA requires only one menu associated with capturing and transmission, and the receiving PDA also involves only one PDA menu associated with image display. Many direct-screen photographing methods using PDAs with either an external or a built-in digital camera that enables direct digital capturing of the PC screen have been researched.[5,6] They can achieve timely transmission with easy operation, but the image distortion occurring during the capturing process compromises the high-quality display necessary for radiological images.

When a direct method of photography is used, image distortion can be caused by image compression losses or distorted image acquisition that is influenced by the manual photographing process. Because image compression cannot be avoided for the timely transmission of radiological images over a mobile network of limited bandwidth, the distortion of image acquisition should be carefully managed. Camera shaking, monitor reflection, environmental illumination, and inaccurate camera focusing can affect the amount of distortion. Photographing by an experienced user and careful manipulation of environmental illumination can reduce the amount of distortion. However, those conditions cannot be met in many emergency situations. Therefore, undistorted image acquisition is important in maintaining the high-quality display for the correct diagnosis and interpretation of radiological images. The program-based screen-capturing application running on the computer as a background program can completely remove the distortion from the image acquisition.

Rapid display of the radiological images on the consultant's PDA screen is critical in the application of emergency teleradiology. Multiresolution transmissions can be exploited by using the resolution differences between the PC screen and the PDA screen. Because the display resolution of the PDA is lower than that of the PC, the number of pixels to be displayed can be associated with the resolution of the PDA. Therefore, the downsampling of full-resolution image matching to the PDA resolution can speed up the image transmission. After displaying the downsampled image for rapid emergency care, the display in its full resolution can be postponed until a zoomed display is requested. These multistep operations with some marginal time enable multiresolution progressive transmission in situations where rapid display is critical.

Besides timely and fine-quality displays of radiological images, location limitations are also important for emergency teleconsultation. Without a loss of generosity, it is desirable for the attending physician in the emergency room to be near the patient (not near the PACS terminal). The local Bluetooth interface between the PACS terminal and the attending physician can overcome many location limitations. Moreover, mobile communication by means of a CDMA phone between the attending physician and the consultant can provide extended mobility to the remote specialist beyond the limited local zone.

The transmission time is related to the bandwidth performance of Bluetooth and CDMA networks. The maximum uplink bandwidth of the CDMA 1× EV-DO and the maximum bandwidth of the Bluetooth network are 153 and 723 Kbps, respectively.[12,8] However, the measured bandwidth of the CDMA 1× EV-DO can vary depending on the movement speed of the remote consultant and the number of users in the same cell. The bandwidth of Bluetooth can differ depending on the distance between the PACS terminal and the attending physician. The measured mean bandwidths for CDMA 1× EV-DO in an urban area surrounded by large buildings without movement and for Bluetooth at a 5-m distance are 120 and 110 Kbps, respectively. Although the difference of the maximum transmission rate between the CDMA 1× EV-DO and the Bluetooth networks is significant, the measured mean bandwidths for both networks are similar. Therefore, the penalty associated with the inclusion of the Bluetooth interface is to spend about twice as much time as the direct photographing method in which only transmission over CDMA 1× EV-DO is necessary. Additionally, some factors should be considered to prevent the popular use of the proposed method. This method cannot be applied in small hospitals without PACS because of the requirement of a PACS installation in the emergency room. The display format and pattern on the consultant's PDA are inherently limited by those on the PACS terminal because of the screen-capturing process although some manipulation functions can supplement that limitation. Finally, data protection is more difficult because of inherent weaknesses in air interfaces. Therefore, a protection mechanism should be properly included in the designed system.

CONCLUSION

In conclusion, we designed a new PDA–PET system by combining PDA–phone-based cellular communication with Bluetooth-interfaced local wireless links. The mobility and portability due to PDA and wireless communication can provide effective means of emergency teleconsultation without limiting physicians to fixed locations. Moreover, this system enables the synchronized radiological image sharing seen on the PACS terminal between the attending physician in the emergency room and the remote specialist to be transmitted without distorted image acquisition. To enable rapid and fine-quality radiological image transmission over a cellular network in a secure manner, the progressive compression and security mechanisms are incorporated. The proposed system was tested over a CDMA 1× EV-DO network to evaluate the performance and to demonstrate the feasibility in a real-world setting. Regarding the presentation performance as measured mean time, the low-resolution image fitted to the PDA screen resolution can be transmitted within 7.2 s for fast emergency assessment and for immediate information in emergency situations and for surgical and medical decision making, whereas fine-resolution image matching to the PACS screen can be updated within 25.3 s with a compression ratio of 10 for later in-depth inspection by zooming.

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