In recent years, ubiquitous computing technologies have been applied in the field of medicine. Especially radio frequency identification (RFID) and small sensor networks could provide information about medical practices and patient status in order to prevent malpractices and improve the quality of medical care. As an example of this application, we developed a new system, named “a smart stretcher,” which continuously monitors the patient’s vital signs and detects apnea during transfer within a hospital. This system consists of a small air-mat type pressure sensor measuring both heart rate and respiration rate and a wireless network transmitting these vital data as well as patient ID to an alerting system to notify hospital staff of patient emergencies. Results of experiments in a clinical setting indicated that the system was reliable in continuous respiration monitoring and detection of apnea during patient transfer on the stretcher; however, detection of heartbeat rate was practically difficult because of the motion noises. Moreover patient ID and location were also correctly detected in real time. These results suggested the feasibility of our system for real clinical use.

Key words: Medical errors, Patient monitoring, Safety of medical care, Wireless Location detection, RFID

Introduction

Advances in ubiquitous communication technologies, such as radio frequency identification (RFID) and small sensor networks, are giving rise to new applications in the various fields. In the medical field, especially in hospitals, these ubiquitous communication technologies can improve the safety of medical treatment in order to prevent malpractice and improve the quality of medical care. Various measures to prevent medical errors by using checklist or repetition of the orders have been put in place already, but medical errors cannot be eliminated by human effort alone. The utilization of ubiquitous communication technology is expected to cover “non-computerized gaps” in medical practice where conventional hospital information systems have not been sufficiently effective.

The application of ubiquitous communication technologies in medicine ultimately aims to realize an “intelligent environment” within the hospital, in which the physiological status and behavior of patients are continuously monitored in order to provide the best medical care at any time and at any location within the hospital, with security and safety. As an example of an intelligent hospital environment, we focused on emergency management during patient transfer in hospital. In operating rooms, emer-
emergency rooms, intensive-care unit (ICU) or in some cases, even in ordinary wards, patients can be readily monitored for changes in vital signs, but during their transfer, the physiological status of patients is often not monitored. This may result in medical accidents. Monitoring of respiration is one of the crucial aspects in medical treatment.

In this study, we developed a new wireless system named “a smart stretcher,” which continuously monitors the patient’s vital signs and detects apnea during transfer within a hospital. The main purpose of the system is to prevent medical errors such as the accidental overlooking of patient emergency status and misidentifications of patients. Especially, we focused on alerting patients’ apnea to medical staff while the patient is being transferred within the hospital.

The monitoring system consists of an air-mat type supersensitive pressure sensor measuring heart rate and respiration rate and an ad hoc wireless communication ZigBee network that transmits these vital data to the hospital LAN and to an alerting system to notify hospital staff in case of an emergency. The patient’s ID, read from an RFID wristband, is also transmitted to the alerting system to prevent misidentification of the patient.

We conducted experiments to estimate the feasibility of this wireless monitoring system in a real clinical situation. Our goal was to examine whether the system could detect apnea during patient transfer on a stretcher within the hospital.

System Description

Main components of the smart stretcher system

Three measurement devices are incorporated in the stretcher: the first device measures vital signs, such as heart and respiration rate for detecting apnea; the second provides automatic patient ID recognition; and the third detects patient location within the hospital.

The three kinds of patient information provided by these three devices are transmitted by a wireless network system incorporated in the stretcher, implemented with ZigBee. The ZigBee signals of the patient’s vital signs emitted from the stretcher’s monitoring system are received by ZigBee routers distributed within the hospital (e.g., on corridor ceilings). The routers communicate with each other to form an ad hoc network, a node of which is connected to a PC that serves as a gateway to the hospital information system.

The measurement devices work together to monitor the patient’s physiological status, and when an emergency such as apnea is detected, information about the emergency is transmitted to the alerting system in the ward (Fig. 1).

Fig. 1. System configuration of the smart stretcher
**Vital sign-monitoring system**

The vital sign-monitoring system incorporated in the smart stretcher continuously measures the minute vibrations of the patient’s body by means of a super-sensitive air-mat type sensor and decomposes these signals into respiration frequency and heartbeat frequency components. This air-mat type sensor has already demonstrated its validity and precision in detecting respiration rate and heartbeat\(^7\). To make sure the validity of the air-mat type sensor measurement during the transfer of the stretcher, we compared the respiration and heartbeat signal measured by the air-mat type with that of a strain sensor for respiration rate and that of a pulse oximeter for heart rate.

The vibration signals thus measured by the air-mat type sensor were analyzed with a fast fourier transform (FFT) analysis, which decomposes the temporal vibration signals into sum of the oscillatory components having various frequencies, then the frequency components corresponding to heartbeat and respiration rate were filtered out respectively.

The results of the measurements of both respiration and heart rate are transmitted every 15 s through the ZigBee wireless node in the stretcher. The data are displayed on the computer screen of the medical terminal in the ward. The apnea warning system is included in this monitoring system.

**Apnea warning system**

The apnea-warning algorithm was developed to detect respiratory arrest when the amplitude of the respiratory waveform falls below a predetermined threshold from a moving baseline, temporally averaged over the last five sampling points.

When it detects apnea, the system transmits a warning signal to the monitoring system of the stretcher, the nurse’s PDA, and terminals in the hospital information system. Thus, not only does the monitoring system of the stretcher emit an apnea warning, but it also simultaneously sends alerts to the nurse’s PDA and the nurse station PCs in the ward. An example of the screen display of a nurse’s PDA is shown in Fig. 2. The patient’s name, measurement time, respiratory rate, heart rate, and respiratory state are displayed at 15-s intervals. When apnea is detected, a red warning display appears and the system emits a warning alarm. The nurse who is transferring the patient recognizes the need for emergency care based on these warnings and calls the patient’s doctor immediately.

![Fig. 2. Screenshot of the nurse’s PDA](image-url)
**Automatic patient ID recognition system**

The patient’s ID information is stored in the RFID tag incorporated in the left wristband, and an RFID reader is located on the left side of the stretcher, which recognizes the patient ID automatically. Other patient information is not directly stored in the RFID tag, but is retrieved from the database using the tag’s UID (unique ID peculiar to the tag).

The RFID reader starts the process of reading the patient’s ID when the “bed-leaving” sensor attached to the stretcher detects that a patient is on board the stretcher. The RFID reader is connected to the ZigBee network. If the patient’s ID data are successfully detected, the RFID reading system emits one beep. If a reading error occurs, such as when no ID information is detected or if two or more different patient IDs are read within a given period, the system emits a continuous beep tone. The RFID reader uses the polling mode, whereby the data of a tag are read only within a fixed period, usually set to 30 s. If the reader fails to detect the patient’s ID, it retries to read it for another 30 s.

**Location detection system using the ZigBee network**

To detect the location of the patient and stretcher in real time and to pass this information to other medical staff in the event of a patient emergency, a location detection system is integrated with the ad hoc ZigBee network within the hospital. A received signal strength indicator (RSSI) system is used, which estimates the location according to the signal intensity received by the distributed ZigBee location routers in the hospital corridors. The ZigBee wireless tag attached to the stretcher transmits a unique ID and wireless signal to all ZigBee location routers at 10-s intervals.

Each ZigBee router has a known location. Each of the routers receives the signals from the ZigBee node of the stretcher and transmits the node tag ID attached to the stretcher, and the intensity of the signal received from the ZigBee node, together with its own ZigBee router ID, to the ZigBee gateway and the hospital LAN. The patient’s location is estimated by identifying the ZigBee router that has the greatest signal intensity. The ZigBee routers constitute an ad hoc mesh network that transmits location information reliably to the gateway (Fig. 3).

![ZigBee network configuration](image)

**Fig. 3.** The ZigBee mesh network for detecting the location of the patient on the stretcher
Clinical feasibility experiment

We conducted a feasibility experiment with the smart stretcher in an actual clinical setting. In the experiment, three subjects, two males and one female, each took the role of a patient being transferred on the stretcher. First, the subjects lay down on the smart stretcher at an angle of 45 degrees and wore a strain sensor on their abdomens and a pulse oximeter on their ear lobes for obtaining respiration and heartbeat reference signals. Also, they wore an RFID wristband on their left hands for identification recognition.

Second, the readability of the wristband patient ID was examined. The distance at which the patient wristband ID could be recognized by the RFID reader located on the left side of the stretcher was measured. The RFID system used and the experiment environment are shown in Fig. 4. We changed the reading conditions, such as the types of tag, positions of the RFID reader antenna, and posture of patients, and in each case, we measured the maximum readable distances from the reader antenna installed on the left side of the stretcher. Third, the subject on the stretcher was transported at a speed of 4.5 km/hr, and was asked to stop breathing intentionally in the meantime to investigate whether the monitoring system would detect the apnea in spite of the movement of the stretcher and would emit a warning signal. We measured apnea times of three subjects by using the smart stretcher’s sensor and a strain sensor. For the setting, of the experiment we installed five ZigBee routers and one gateway located at regular intervals on the ceiling of a hospital corridor. Two members of the hospital staff carried the subject on the smart stretcher in the hospital corridor for 80 m. We monitored patient location on the floor map display of the terminal connected to the ZigBee network.

Results

Readability of Patient ID

In almost all cases, the RFID was recognized within 15 s after the reader started and the patient ID was displayed on the monitoring screen in real time. Readable distances from the RFID antenna (left side of the stretcher and under the mat) are shown in Table I. Mat thickness was 55 mm. The readable distance limits for patient ID increased in proportion to tag size. There was no difference in readable distance.
between the patient positions of face-up and semi-sitting. The readable distance of the RFID reader placed on the left side of the stretcher was much better than when it was under the mat (Table I). Identification was most reliable when the patient’s hand wearing the RFID wristband was positioned straight along the edge line of the stretcher; identification was difficult when the hand was not in that position. When two IDs were read at the same time, the patient ID was displayed as “unknown” and the system emitted a beep to alert medical staff of the need for re-reading.

**Detection of Apnea**

Reliable measurements were obtained for respiration rate during transfer for each of the three subjects. One of the measurement results is shown in Fig. 5. Heart rate frequency is within 0.5-2 Hz and respiration rate is within 0.1-0.5 Hz in a normal subject. The result of an FFT analysis of the data in Fig. 5 is shown in Fig. 6. The peaks of respiration frequency were within 0.1-0.5 Hz in all subjects. In all cases, heart rate frequency was mostly within 0.5-2 Hz, but the results had a few high peaks in the frequency spectrum that were thought to be caused by motion noise during the movement of the stretcher. The measured respiration waveforms indicated the apnea by flattening out for about 10 s.

The respiration signals corresponded with the spectrum of respiration by reference. However, the spectrum of heartbeat did not correspond with the highest peak of the spectrum but second higher spectrum. We believe that these results occurred due to the stretcher’s movement noise. However, we confirmed that the respiration rate could be correctly detected by the vital-monitoring system although heartbeat rate could not obtained in this setting.

**Table I The results of readable distances of patient ID**

<table>
<thead>
<tr>
<th>Tag type</th>
<th>Maximum Readable distance</th>
<th>RFID Antenna</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tag A</td>
<td>~60 mm</td>
<td>60 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12 mm</td>
</tr>
<tr>
<td>Tag B</td>
<td>~250 mm</td>
<td>128 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>73 mm</td>
</tr>
<tr>
<td>Tag C</td>
<td>~350 mm</td>
<td>135 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>80 mm</td>
</tr>
</tbody>
</table>

**Fig. 5.** The measurement results during the smart stretcher’s transfer
The apnea detection method worked well as shown in an example of the respiratory waveforms for detecting apnea during transfer in Fig. 7. The measured respiration waveforms indicated the apnea by flattening out for about 10 s. By referencing the waveform of the strain sensor, it was considered that the apnea-warning algorithm could effectively detect correct apnea time.

We measured the detection rate for apnea by the smart stretcher. The results are summarized in Table II. The apnea of subject A and B were almost completely detected. However, that of subject C was detected at 77.1% because of motion noise that raised the respiratory signal higher than the threshold consequently, and as a result it was regarded that the subject was...

Fig. 6. The results of FFT analysis of fig 5 data

Fig. 7. The respiratory waveforms for detecting apnea during a transfer
breathing. Overall, apnea could be detected at the rate of 99.1% on average with all subjects. Moreover through the ZigBee wireless network, the patient’s name, respiration rate, and heart rate were correctly displayed on the PDA screen. The apnea warning alert and the warning screen on the PDA were also displayed almost in real time.

Detection of Location of the Smart Stretcher

The location detection system showed good performance in providing the correct location in real time (Fig. 8). Radial distance of detecting location was 15 m. The range of error was ±10 m. Serious errors and delays in the display of the detected location were not observed in this location detection experiment.

Discussion

From these preliminary results, the patient’s vital signs, ID, and location could be obtained in real time during transfer of a patient on the smart stretcher. Using three kinds of information, the smart stretcher may be able to contribute to medical safety, especially the oversight of the patient’s physical status, prevention of misidentification of patient, and miscommunication with other medical staff in the clinical setting.

There are some previous studies of the use of RFID for preventing errors in medication\(^8\) and in the identification of patients and medical staff.\(^9\) However, other than a study using a location detection system, these studies have concerned only patient’s rooms or operation rooms.\(^10\)\(^-\)\(^12\) Medical errors can occur at any place in a hospital. The stretcher system described here can be

### Table II The detection rate of apnea

<table>
<thead>
<tr>
<th>Subject</th>
<th>Respiratory arrest times</th>
<th>Detection times</th>
<th>Detection ratio [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (70kg)</td>
<td>8</td>
<td>8</td>
<td>100.0</td>
</tr>
<tr>
<td>B (65kg)</td>
<td>15</td>
<td>14</td>
<td>93.0</td>
</tr>
<tr>
<td>C (55kg)</td>
<td>7</td>
<td>7</td>
<td>100.0</td>
</tr>
<tr>
<td>Total</td>
<td>35</td>
<td>31</td>
<td>91.1</td>
</tr>
</tbody>
</table>

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**Fig. 8.** Screenshot of the location detection application (PC screen)
PC: Dell (PP21L, OS: windows XP, Memory: 512Mbyte)
used irrespective of the location of the patient. Moreover, it monitors the patient’s state automatically without the need for staff to attach medical devices to the patient. However, measurements were sometimes less precise because of various environmental factors. Nevertheless, the smart stretcher system has the advantage of being able to use easily without attaching any sensors to patients for monitoring their vital signs and transmit the data in real time. The physiological status and behavior of patients are constantly monitored to facilitate safe medical care anytime, anywhere in the hospital. We need further detailed investigation of the factors that influence the precision of the measurements to improve the recognition performance of RFID and the measurement of vital signs.

With regard to the results of location detection, individual stretcher locations were not detected accurately because the location error was about 10 m. We think that accuracy can be increased by adjusting the system settings to fit the specific hospital environment where it is being used.

This system demonstrates the feasibility of using widely used technology as part of a preventive measure for medical malpractice. However, it is somewhat difficult to use this system in clinical practice as it is, because of problems such as cost, system operation, and network infrastructure. We consider that this study is another step toward realizing a smart medical space with security and safety.

Acknowledgments

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