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TECHNICAL NOTE

A non-contact vital sign monitoring system for ambulances using dual-frequency microwave radars

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Abstract We developed a novel non-contact monitoring system to measure the vital signs of casualties inside a moving ambulance. This system was designed to prevent exposure of patients to infectious organisms under bio-chemical hazard conditions. The system consists of two microwave radars: a 10-GHz respiratory-monitoring radar is positioned 20 cm away from the surface of the isolator. The 24-GHz cardiac-monitoring radar is positioned below the stretcher underneath the isolator. The subject (22.13 ± 0.99 years) was placed inside the isolator on a stretcher in the simulated ambulance. While the ambulance was in motion at a speed of approximately 10 km/h, the heart rates determined by the cardiac-monitoring radar correlated significantly with those measured by ECG ($r = 0.69$, $p < 0.01$), and the respiratory rates derived from the respiratory-monitoring radar correlated with those measured by the respiration curves ($r = 0.97$, $p < 0.0001$). The proposed system appears promising for future on-ambulance monitoring of the vital sign of casualties exposed to toxins.

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1 Introduction

We developed a non-contact vital sign monitoring system using dual-frequency microwave radars (10-GHz and 24-GHz) for measuring the vital signs of casualty patients inside a moving ambulance. While the ambulance was in motion and when it was stopped and idling, this system is able to simultaneously measure the respiratory and heart rates of patients from outside an isolator without touching the patient. The isolator is used to protect patients from contamination or cross-contamination during or after a catastrophic event, and to transport patients who have been exposed to toxic chemicals or infectious organisms. We have previously reported on the use of this non-contact method to monitor the heart and respiratory rates of experimental animals exposed to toxic materials or in a hypovolemic state in order to determine the pathophysiologic condition of the subjects, such as whether they had been exposed to toxins or were experiencing shock induced by hemorrhage [7, 8]. We have previously also reported the non-contact method using a ceiling attached microwave radar to monitor the respiratory rates of subjects in bed through thick bedding [10] and attached it to the back of a chair to monitor the change of autonomic activation [9]. The method can be performed without thick bedding removal because microwave radar, which has been studied for use in locating human subjects buried under earthquake rubble [1–3, 6], has no trouble penetrating thick bedding.

The noninvasive sensing techniques have been developed in order to measure the human vital signs. Several attempts of noninvasive pulse monitoring have been conducted using a strain gauge [4] and pressure sensors [5]. Wang et al. [11] have reported the method to measure the heart beat and the respiration from the subject's back using a polyvinylidene fluoride film (PVDF) piezoelectric polymer sensor. These non-electrode methods are useful for the patients with severe burn. They have limitations endemic to contact methods.

We tested the ability of the proposed non-contact vital sign monitoring system to measure the respiratory and heart rates of healthy human subjects from outside an isolator installed in a simulated ambulance, both while the ambulance was in motion and when it was stopped and idling.

2 System design and testing of the non-contact vital sign monitoring system

2.1 Non-contact vital sign monitoring system

The prototype non-contact vital sign monitoring system consists of two microwave radars: a 10-GHz microwave radar unit for respiration monitoring, and a 24-GHz microwave radar unit for cardiac monitoring. Each radar has normal output power of 7 mW (maximum 10 mW), antenna gain of 10 dBi and diffusion angle of approximately 40°. The system is controlled by a personal computer with custom sampling and display programs written in LabVIEW (Version 8, National Instruments Co., USA). The 10-GHz microwave radar incorporates an oscillator and microwave radar antenna into a cylinder (7 cm in diameter and 5 cm thick, with a 2.9 × 4.2 cm size quadra-pole plane antenna). The 24-GHz microwave radar is a small rectangular box (8 × 5 × 3 cm, with a 1.1 × 1.2 cm size quadra-pole plane antenna) containing an oscillator and a microwave antenna.

The 10-GHz microwave radar for respiratory-monitoring radar is attached to upper surface of the metal frame which encloses an isolator (Casualty Care System, CCS^{TM}, Gentex Co., USA). The isolator is designed to protect casualties from contamination during or after a catastrophic event and to transport patients who are exposed to toxic chemicals or infectious organisms. This radar is positioned 20 cm away from the surface of the isolator, and receives reflected microwaves modulated by pulmonary chest wall motions. The 24-GHz microwave radar for cardiac-monitoring is positioned below the stretcher underneath the isolator. This radar monitors the microwave reflection modulated by cardiac motions from the dorsal side of the subject, as shown in Fig. 1.

The analog outputs of the two microwave radars are transferred to a personal computer through an A/D converter and analyzed in real time. The respiratory and heart rates, as well as the cardiac and respiratory curves from both the non-contact (microwave radar) and contact

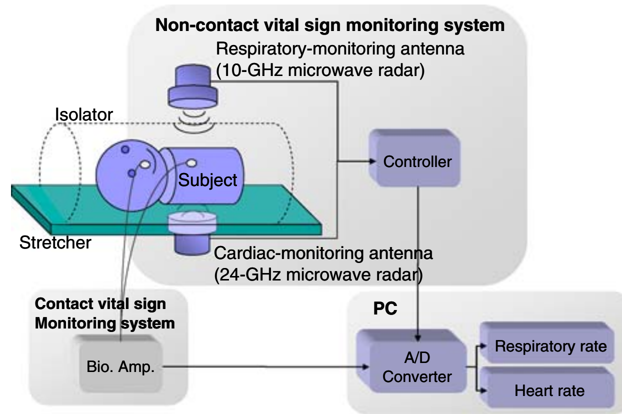

Fig. 1 Schematic diagram of the experimental setup to test a non-contact vital sign monitoring system on a simulated ambulance

(electrocardiogram and respiration sensor) instruments are displayed on a graphical terminal in real time (Fig. 2).

2.2 Experiments and Setting

The experiments were conducted on eight healthy male subjects ranging in age from 21 to 24 years old (22.13 ± 0.99 years). A minivan with a 2,800 cc engine (Delica, Mitsubishi Motor Co., Japan), which is sometimes used as an ambulance, simulated an ambulance in this experiment. The healthy subject was placed inside the isolator on a stretcher, which was placed in the loading space of the simulated ambulance. We monitored the respiratory and the cardiac motion of the subjects from outside of the isolator.

For reference, the patient's precordial electrocardiogram (ECG) was measured with electrodes, and the respiratory curve was measured using a thermistor respiration sensor (TR511G, Nihon Koden Co., Japan) inserted into a nasal cavity. Both contact monitoring systems were connected to a multi-channel telemetry system (WEB-5500, Nihon Koden Co., Japan).

This system was tested while the simulated ambulance was in motion as well as when it was stopped with the motor idling. During each test, the ambulance drove to the end of a 200-m straight course paved with asphalt and returned to the departure point, repeatedly, at a speed of approximately 10 km per hour for about 10 min. During the examinations, the isolator was properly ventilated using its attached air pump.

The study protocol was reviewed and approved by the Committee on Human Research of the Faculty of System Design, Tokyo Metropolitan University.

2.3 Analysis

The output signals from the 24 and 10-GHz microwave radars and reference outputs were sampled by the A/D

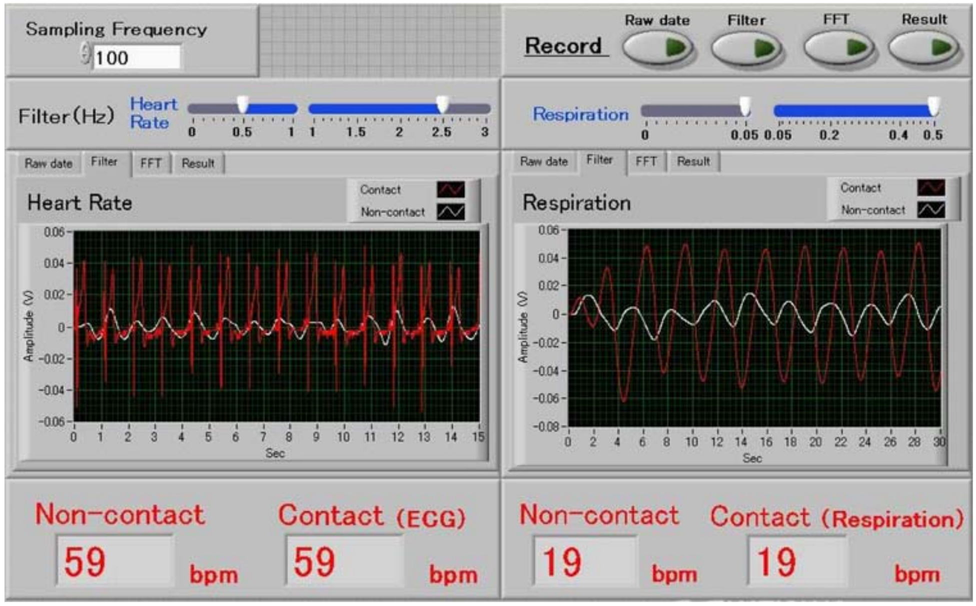

Fig. 2 Graphic display of the custom sampling and display program written in LabVIEW. Fast Fourier Transforms of the microwave radar analog outputs were used to derive the respiratory and heart rates (while the simulated ambulance was stopped with the motor idling)

converter with a sampling interval of 10 ms. Band pass filters were used for both radar outputs to reduce noise and interference. The band pass filter for the 24-GHz microwave radar for cardiac-monitoring was set between 0.5 and 2.5 Hz. For the 10-GHz microwave radar for respiratory-monitoring, the filter was set between 0.05 and 0.5 Hz. These band pass filters cover ranges 30–150 heart beats per minute and 3–30 respirations per minute for the respiration, respectively. After band pass filtering, a fast Fourier transform (FFT) was conducted with a Hanning window. Both respiratory and heart rates were derived from the peak of the FFT spectrum. The correlation coefficient between the heart rate acquired by non-contact vital sign monitoring system and contact monitoring system was examined.

Statistical analysis was performed using StatMate III Software (ATMS, Japan).

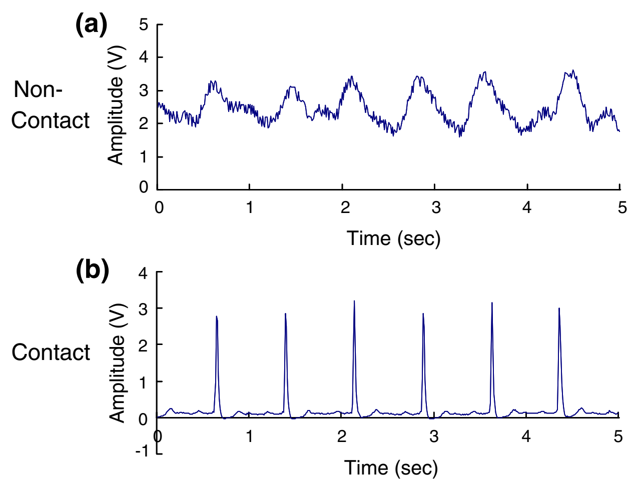

Fig. 3 While the simulated ambulance was in motion, the 24-GHz microwave radar output (**a**) exhibits cyclic oscillations with human cardiac motion which correspond to the RR intervals of the ECG (**b**)

3 Results

While the simulated ambulance was in motion, the 24-GHz microwave radar output exhibits a sample of a cyclic oscillation with a period of 5 s that corresponds to the cardiac oscillation measured by ECG (Fig. 3). We found that the 24-GHz microwave radar output has similar peak intervals to the ECG. In the 10-GHz microwave radar output, a sample of a cyclic oscillation with a period of 20 s is observed, which corresponds well with the respiratory curves measured by the thermistor respiration sensor (Fig. 4).

The respiratory and heart rates determined by the microwave radars using our custom program were compared with those measured by the contact methods. The results are shown in Fig. 5 for the case when the simulated ambulance was stopped and idling; the results in Fig. 6 are those for the simulated ambulance in motion.

When the ambulance was stopped, the heart rates determined by the 24-GHz microwave radar correlated significantly with the rates measured by ECG with electrodes ($r = 0.76$, $p < 0.01$) (Fig. 5a). The respiratory rates measured by the 10-GHz microwave radar correlated significantly with the respiratory rates measured by thermistor sensor ($r = 0.98$, $p < 0.0001$) (Fig. 5b).

While the simulated ambulance was in motion, the heart rates determined by the 24-GHz microwave radar correlated significantly with the heart rates measured through

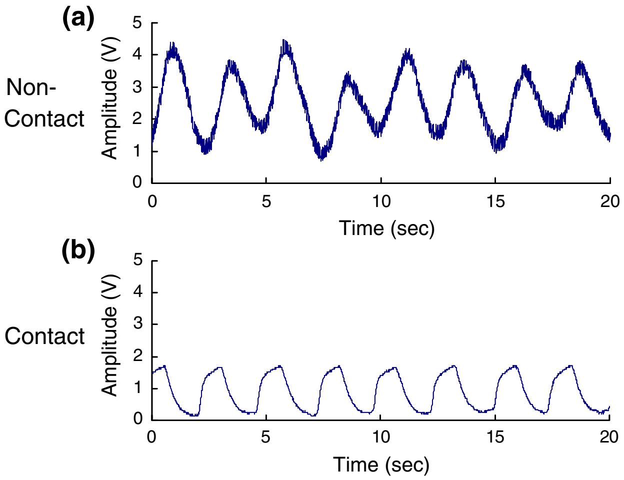

Fig. 4 While the simulated ambulance was in motion, the 10-GHz microwave radar output (**a**) exhibits cyclic oscillations with the respiratory motions of human chest wall, which correspond to the respiratory curves measured by a contact thermistor sensor (**b**)

the ECG with electrodes ($r = 0.69$, $p < 0.01$) (Fig. 6a). The respiratory rates measured by the 10-GHz microwave radar correlated significantly with the respiratory rates measured by the thermistor sensor ($r = 0.97$, $p < 0.0001$) (Fig. 6b). While the simulated ambulance is in motion as well as parked state, the proposed non-contact vital sign monitoring system could measure the respiratory and heart rates of healthy human subjects from outside an isolator installed in a simulated ambulance.

4 Discussion

Using a dual-frequency microwave radar system, we monitored the vital signs of subjects from outside of an isolator placed on a stretcher installed in a simulated ambulance. We found that the system could monitor heart and respiratory rates of subjects: the 24-GHz microwave

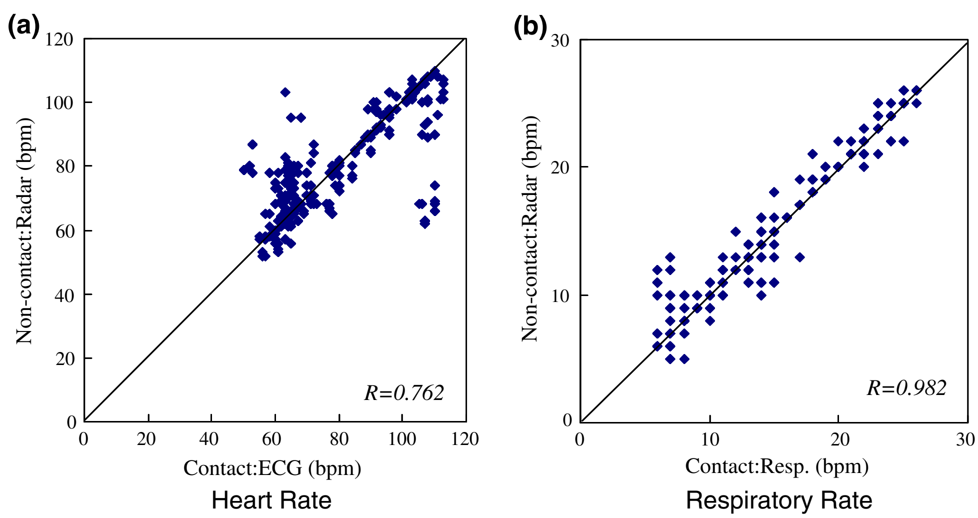

Fig. 5 Comparison between contact and non-contact measurement of heart (**a**) and respiratory (**b**) rates of healthy volunteers while the simulated ambulance was stopped and idling. These data show a significant correlation between the rates determined by the microwave measurement and by the reference monitors (ECG and thermistor sensor) (**a** $r = 0.76$, $p < 0.01$; **b** $r = 0.98$, $p < 0.0001$)

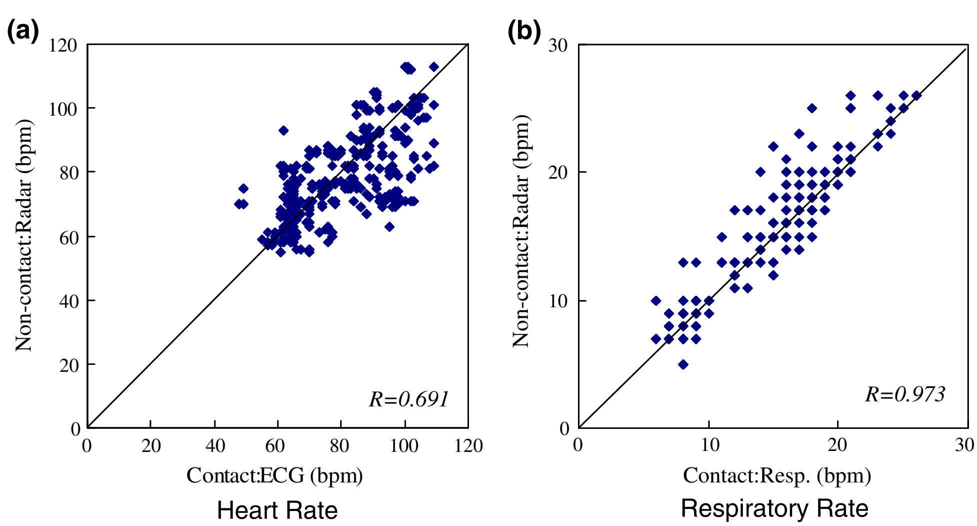

Fig. 6 Comparison between contact and non-contact measurement of heart (**a**) and respiratory (**b**) rates of healthy volunteers while the simulated ambulance was in motion. These data show a significant correlation between the rates determined by the microwave measurement and by the reference monitors (ECG and thermistor sensor) (**a** $r = 0.69$, $p < 0.01$; **b** $r = 0.97$, $p < 0.0001$)

radar output exhibits a cyclic oscillation that corresponds to cardiac motion, and the 10-GHz microwave radar output exhibits cyclic oscillations which correspond to the respiratory motions of the chest wall. Both the 24 and 10-GHz microwave radar outputs contained background noise which can be attributed to the vibration of the ambulance motor which is present both when the ambulance is moving and when it is stopped.

The isolator used in these experiments is designed to protect casualties from contamination or cross-contamination during or after a catastrophic event and to transport patients who are exposed to toxic chemicals or infectious organisms. The isolator provides a barrier to both chemical and biological materials. Generally, the isolator is equipped with a medical interface bulkhead for intravenous lines, but each treatment or monitoring technique requiring patient contact is a potential route for secondary exposure of medical and rescue personnel to toxic chemicals and infectious organisms. Our system can monitor the vital signs of casualties without any risk of secondary exposure. Furthermore, it does not require clothing removal and it can monitor patients before decontamination procedures have been completed.

This non-contact vital sign monitoring system may be capable of monitoring the respiratory and heart rate increase caused by infection with mortality risks. The respiratory and heart rates are indices used for the diagnosis of systemic inflammatory response syndrome (SIRS), a significant predictor of multiple organ failure (MOF). The respiratory and heart rates are parameters to diagnose SIRS. In SIRS criteria, respiratory rate is higher than 20 breathes per minute, heart rate is greater than 90 beats per minute [12].

Without requiring clothing removal and able to be used before decontamination procedures from outside the isolator loaded on to an ambulance, our system appears promising for future prehospital application in monitoring casualty patients and reducing the risk of secondary exposure to toxic chemicals or infectious organisms, for example, in the case of large-scale disasters.

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