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A novel apparatus for non-contact measurement of heart rate variability: a system to prevent secondary exposure of medical personnel to toxic materials under biochemical hazard conditions, in monitoring sepsis or in predicting multiple organ dysfunction syndrome

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Abstract

Background. – The impaired balance of the low-frequency/high-frequency ratio obtained from spectral components of RR intervals can be a diagnostic test for sepsis. In addition, it is known that a reduction of heart rate variability (HRV) is useful in identifying septic patients at risk of the development of multiple organ dysfunction syndrome (MODS). We have reported a non-contact method using a microwave radar to monitor the heart and respiratory rates of a healthy person placed inside an isolator or of experimental animals exposed to toxic materials.

Apparatus design and testing. – With the purpose of preventing secondary exposure of medical personnel to toxic materials under biochemical hazard conditions, we designed a novel apparatus for non-contact measurement of HRV using a 1215 MHz microwave radar, a high-pass filter, and a personal computer. The microwave radar monitors only the small reflected waves from the subject's chest wall, which are modulated by the cardiac and respiratory motion. The high-pass filter enhances the cardiac signal and attenuates the respiratory signal. In a human trial, RR intervals derived from the non-contact apparatus significantly correlated with those derived from ECG ($r = 0.98$, $P < 0.0001$). The non-contact apparatus showed a similar power spectrum of RR intervals to that of ECG.

Conclusions. – Our non-contact HRV measurement apparatus appears promising for future pre-hospital monitoring of septic patients or for predicting MODS patients, inside isolators or in the field for mass casualties under biochemical hazard circumstances.

Keywords: Non-contact; Microwave radar; Heart rate variability (HRV); Sepsis; Multiple organ dysfunction syndrome (MODS)

1. Introduction

The impaired balance of the low-frequency/high-frequency ratio obtained from spectral components of RR intervals can be a diagnostic test for sepsis [1]. Furthermore, it has been reported that heart rate variability (HRV) reduction is useful in identifying septic patients at risk of development of multiple organ dysfunction syndrome (MODS) [2]. We have previously reported a non-contact method using microwave radar for monitoring the heart and respiratory rates of a healthy person placed inside an isolator or of experimental animals exposed to toxic materials [3,4]. In order to diagnose sepsis without touching a patient, with the purpose of preventing secondary exposure of medical personnel to toxic materials under biochemical hazard conditions, we designed a novel apparatus for non-contact measurement of HRV using a microwave radar.

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2. Design of apparatus for non-contact measurement of HRV

We designed a novel apparatus for non-contact measurement of HRV using a 1215 MHz microwave radar. The apparatus consists of a microwave radar (Tau Giken, LDR-1, Yokohama), an antenna box, a high-pass filter, an AD converter (MFU98-401B, Micro Science, Tokyo), and a personal computer (Fig. 1). The microwave radar generates a very stable microwave signal at 1215 MHz with a maximum output power of 70 mW. The microwave radar system eliminates reflected microwaves from stationary objects around the antennas, and monitors only the small reflected waves from the subject's body because these waves are modulated by the subject's body motion [3–8]. A microwave antenna box (37 × 15 × 5 cm) with two microstripe antennas (radiating and receiving antennas, 70 mm in diameter) was connected to the microwave radar. The microwave radar output was transferred to the personal computer by the AD converter through a high-pass filter. The cutoff frequency of the high-pass filter was 1.3 Hz. The high-pass filter enhances the signal derived from the cardiac motion and attenuates the signal resulting from respiratory motion, which is a dominant component of the microwave radar output. The sampling interval of the microwave radar output was 1 ms. The RR intervals were derived from the peak intervals of the microwave radar output signal, which was modulated by the high-pass filter. The power spectrum was calculated using the MemCalc software package (GMS, Tokyo) for a 15 s period. MemCalc, which uses the maximum entropy method, needs a shorter data length (sampling duration) than fast Fourier transform (FFT).

3. Testing of the apparatus

The study was approved by an institutional review committee on human studies. After obtaining informed consent, the apparatus was tested on a healthy volunteer (43 years old male). The microwave antenna box was located 40 cm away from the chest wall of the volunteer in a sitting position. As a reference, pectoral ECG was monitored along with the non-contact monitoring. The sampling interval of the pectoral ECG was 1 ms. The power spectrum of RR intervals derived by the non-contact apparatus for 15 s along with the power spectrum of RR intervals derived from ECG for the same period were calculated.

4. Results

The microwave radar output through the high-pass filter shows a cyclic oscillation, which corresponds to the cardiac oscillation (Fig. 1(b) upper). The peaks of the oscillation were delayed by approximately 200 ms relative to the R-wave of the ECG (Fig. 1(b) lower). This time delay can be attributed to the delay caused by the phase shifter of the microwave radar. The RR intervals derived from the ECG and that derived by the non-contact apparatus are shown in Fig. 2(a). They show similar fluctuations, the RR intervals derived by the non-contact apparatus significantly correlated with the RR intervals from the ECG (r = 0.98, P < 0001, Fig. 2(b)). The power spectrum of the RR intervals derived by the non-contact apparatus has a similar power spectrum (Fig. 2(c)) to that of the RR intervals from the ECG (Fig. 2(d)).

5. Discussion

It has been reported that a low-frequency/high-frequency ratio of < 1.0 in HRV can be a diagnostic test for sepsis [1]. Furthermore, it is known that a reduction of HRV is useful in identifying septic patients at risk of the development of

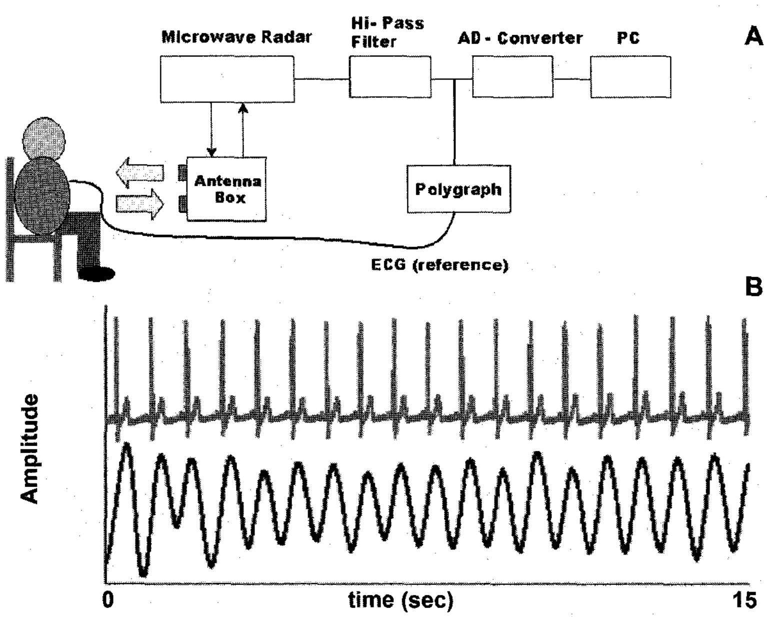

Fig. 1. (a) Schematic diagram of apparatus for non-contact measurement of HRV. (b) Microwave radar output through high-pass filter showing a cyclic oscillation that corresponds to the cardiac oscillation (upper). The peaks of the oscillation are delayed approximately 200 ms relative to the R-wave of the ECG (lower).

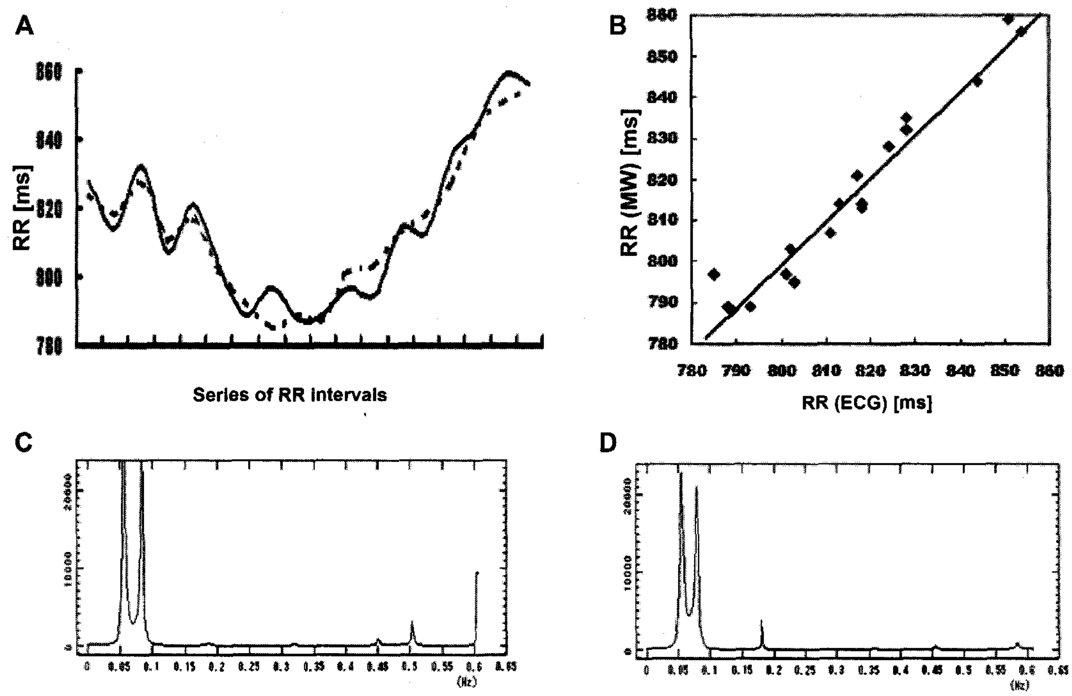

Fig. 2. (a) RR intervals derived from ECG and RR intervals derived from the non-contact apparatus showing similar fluctuations. (b) The RR intervals derived from the non-contact apparatus significantly correlate with the RR intervals from the ECG ($r = 0.98$, $P < 0.0001$). (c, d) The power spectrum of the RR intervals derived from the non-contact apparatus has a similar power profile to that derived from the ECG ((c) non-contact apparatus, (d) ECG).

MODS [2]. Hence, the monitoring of HRV can be used not only as a diagnosis method for sepsis but also as a prediction technique for MODS.

Low frequency variability in RR interval and systolic arterial pressure below 0.1 Hz during head-up tilt tests has been reported in conditions similar to hypovolemic states in humans [9]. Madwed has previously reported that hemorrhage-induced low-frequency oscillations in RR intervals may be primarily mediated by the cardiac sympathetic nerves in dogs. He concluded that hemorrhage-induced oscillations in RR intervals at 0.05 Hz represent the arterial baroreceptor-beta-sympathetic reflex response to underlying arterial pressure oscillations [10]. Our apparatus can monitor the hemorrhage-induced reaction in real time without touching the patient.

Thirteen out of fifteen Keio Hospital emergency room doctors who treated victims of a terrorist attack by a religious cult involving the use of sarin nerve gas in the Tokyo subway in 1995 exhibited symptoms of exposure during the treatment of two victims. Eleven doctors (73%) reported dim vision and eight doctors (53%) had severely miotic pupils (< 2 mm) [11]. Exposure to sarin, which is an acetylcholine receptor blocker may change sympathovagal balance. In addition, using detailed epidemiologic data on severe acute respiratory syndrome (SARS) from Singapore in 2003, it has been estimated that a single infectious case of SARS could infect about three secondary cases in a population that has not yet instituted control measures [12]. In order to prevent secondary exposure of medical personnel to toxic materials under biochemical hazard conditions, our apparatus can monitor HRV without touching the patient. Our apparatus appears promising for future pre-hospital monitoring of nerve gas victims, septic patients or in predicting MODS patients, inside an isolator or in the field for mass casualties under biochemical hazard circumstances.

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