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Human Pulse Detection Using Multiple Silicon Microphones toward Estimation of Physical Condition

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Abstract: An Electret Condenser Microphone (ECM) fabricated by Micro Electro Mechanical System (MEMS) technology, or a silicon microphone chip, was integrated into a multiple sensor apparatus to detect human pulse wave toward estimation of physical condition of our body. Ten of MEMS-ECMs were placed at the forearm of a subject with multi-channel signal amplifier and recorder. As a developing result, it is successfully demonstrated that MEMS-ECM sensors are sensitive enough to detect human pulse wave. Moreover, it is suggested that an internal physical condition in relation to an activity of sympathetic/parasympathetic nervous system might be estimated by comparing pulse signals derived by this multiple MEMS-ECM sensors.

Key words: Silicon microphone, MEMS, electret condenser microphone, pulse wave, autonomic nervous system

INTRODUCTION

An Electret Condenser Microphone (ECM) fabricated by Micro Electro Mechanical System (MEMS) technology, or a silicon microphone chip (Fig. 1a), was integrated into a multiple sensor apparatus to detect human pulse wave toward estimation of physical condition of our body.

Human pulse which is originally generated by the construction/relaxation of our heart is a pressure wave propagating through blood vessel. It is not merely a signal representing the timing and frequency of the heart beats but it covers useful and important knowledge in clinical scene. Chen *et al.* (2000) developed continuously blood measurement system by referencing the pulse waveform for controlling cuff pressure and the latency of pulse wave. Suzuki and Oguri (2010) proposed cuff less blood pressure estimation using optical pulse wave detection device (Photoplethysmograph: PPG) by introducing soft-computing technique (Suzuki and Oguri, 2010). Sano *et al.* (1985) demonstrated that the human pulse wave form is closely related to the condition of blood vessels, thus, to cardiovascular symptom.

As just described human pulse waveform gives us important clinical knowledge. Moreover the beat-to-beat interval of pulse wave represents autonomous nervous system activation. Many attempts have been made to integrate a pulse detection device into human-machine interaction system, e.g., intelligent vehicle (Healey and Picard, 2005). However, the apparatus for detecting human pulse has not been developed for a long time. PPG is the most common and reliable pulse detection device. However, it can only detect the pulse at the tip top of a finger. It is thus normally used singly (one-channel). By contrast, in this study, we propose a multiple pulse sensing structure by using MEMS-ECMs.

MEMS-ECM is a small microphone assembled by semiconductor production processing. Since, it has an advantage in the size and quality comparing with other ECMs, MEMS-ECM is commonly used in cell phones or other mobile terminals. MEMS-ECM consists of ECM in which electro charged back plate and metal diaphragm forms a micro condenser (Fig. 1b) and CMOS chip in which the signal amplifier, buffer and electro charge pump are integrated in a chip. MEMS-ECM is a silicon condenser microphone chip. In other words it is a pressure sensor with high quality and performance. Further the frequency response of this tiny ECM is

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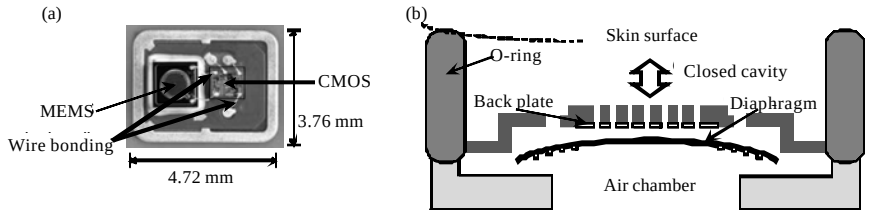

Fig. 1: MEMS-ECM: (a) outline view and (b) ECM architecture

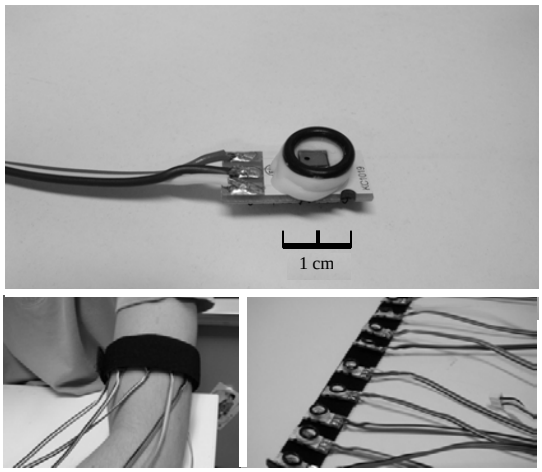

Fig. 2: MEMS-ECM sensors

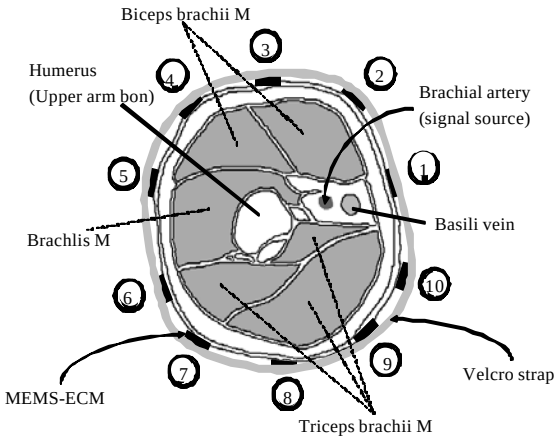

Fig. 3: Arrangement of each MEMS-ECM

theoretically constant in the range of below than resonance frequency as so-called stiffness control. Therefore even though MEMS-ECM was designed to catch audio frequency signals as for a microphone, it can be possible to detect the signal in lower range of frequency which includes the frequency range of the human pulse wave, i.e., 1.4 Hz in the center frequency.

MATERIALS AND METHODS

In this study, we developed a multiple human pulse wave sensing structure by interspacing MEMS-ECM sensors 1 circulatory around the forearm of a subject as depicted in Fig. 2. With regard to MEMS-ECM sensors, a consumer MEMS-ECM, SPM0408HD5 provided by Knowles Acoustics, LLC., USA/Japanwere introduced. As shown in Fig. 2, a rubber diaphragm were attached onto each MEMS-ECMsso as to form a closed cavity inside of the air space covered by the skin and the diaphragm of MEMS-ECM which is fundamental to detect the pulse signals.

Analogue signal acquired by each MEMS-ECM was transferred and digitized by versatile bio-signal amplifier and recorder system (BIOPAC MP150 system, BIOPAC System Inc.). The signal sampling of ten of MEMS-ECMs was made synchronously at the resolution in 16 bit and at the rate of 4000 Hz (sampling rate).Proprietary developed software for the bio-signal amplifier (AcqKnowledge 3.9., BIOPAC System Inc.) was used for further analysis.

As shown in Fig. 3, ten MEMS-ECM sensors were placed at a regular interval around the forearm of a subject by using Velcro strap. For the purpose of the comparison of bio-signals under envisioned different level of autonomous nervous system activities, the subject were instructed to seat in a chair holding still and breathe (1) normally (hereafter named "Normal" condition), (2) rapidly ("Rapid"), or (3) slowly ("Slow"). The duration of each Normal, Rapid and Slow session were about 1 to 3 min.

RESULTS AND DISCUSSION

Figure 4 shows the typical signals acquired by ten of MEMS-ECMs and the heart beat signal (Electrocardiogram: ECG) for reference. As shown in this figure, each beat of MEMS-ECMs were appeared with a

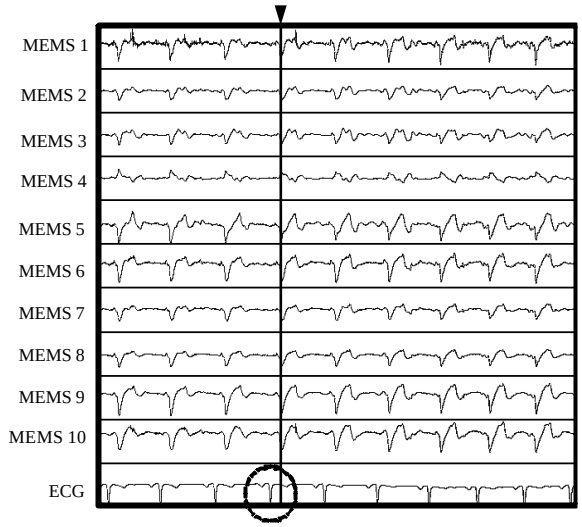

Fig. 4: Recorded pulse signals

certain time later by the heart beat signal, which is 155 ms in average. Since the bio-signal (pulse) detected by MEMS-ECM originally propagated from heart, these time delay at forearm is matter of course.

On the other hand, there seems to beno any difference at all in the beat time (peak time) among MEMS-ECMs on the surface. However, in fact there were slight differences in the beat time as summarized in Fig. 5. Figure 5 shows the time difference between the peak of the heart beat (so called "R-wave" in ECG) and that of MEMS-ECMs. Remarkably this time difference between MEMS-ECM No.1 (denoted "MEMS 1") to ECG is significantly smaller than any other MEMS-ECMs: the time difference is ranged from 6 to 18 msec and 11 msec in average. Since, MEMS 1 was placed at the nearest site from brachial artery where the pulse signal should propagate into the whole forearm (Fig. 3), it is accountable. Generally the pulse wave runs through the artery at the speed of over 10 m sec^{-1} (Ganong, 2003). The result described here successfully demonstrates the sensitivity of MEMS-ECM sensor as the human pulse sensor.

However, regarding with the other signals from the rest sensors there were no remarkable differences among them as shown in Fig. 5. Especially the signals from MEMS 2 or MEMS 10 which were placed at the next to MEMS 1 and thus at relatively near site from the signal source were not so small but rather greater as comparing with that of the other site, such as MEMS 5 for an example. When one looks at the wave form taken by each sensor, the wave forms taken by the sites, e.g., MEMS 2, MEMS 10, MEMS 7 etc, in which the latency from the

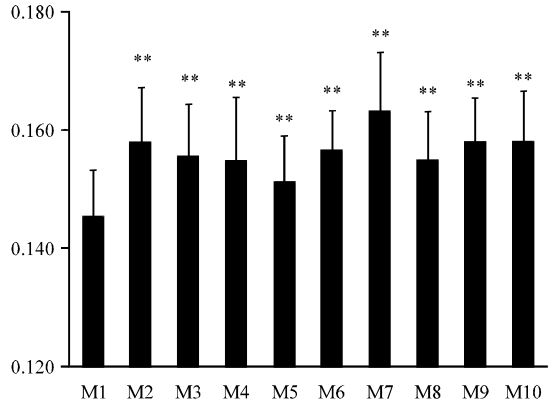

Fig. 5: Latency of MEMS signal from ECG, **p<0.01 vs M1

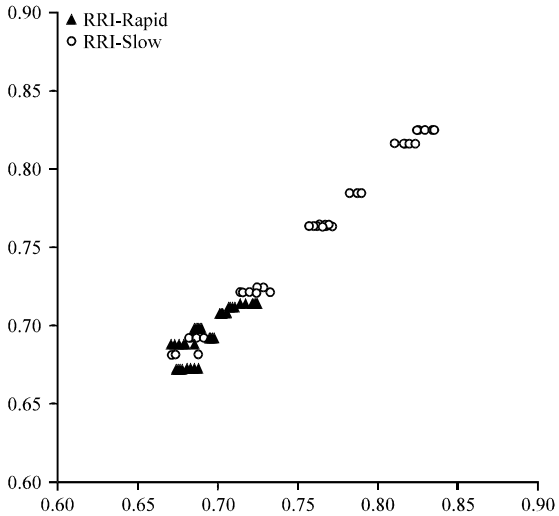

Fig. 6: Scatter diagram between beat-to-beat intervals measured by MEMS-ECM and ECG

heart beat were relatively longer are seems to be rounded. It can be inferred that this round-shaped pulse wave might consist of the original signal and other multiple wave signals which includes (1) the reflection of pulse wave by the upper arm bone (2) the diffraction waves propagating inside the forearm, or (3) other pulse waves generated by minor arteries existing in the forearm, such as radial collateral artery and superior ulnar collateral artery. Unfortunately, we do not have enough experimental results so far to make a relevant explanation about this result. At any rate, MEMS-ECM signal should be modified sensitively reflecting internal structure of the forearm. In other words, it might be possible to observe internal physical condition in our body by referring MEMS-ECM signals from the surface of skin.

Figure 6 shows the correlativity between the beat-to-beat interval of the heart beat (so called R-R interval) and that of corresponding interval of the MEMS-ECMs signals. It should be noted that each value from ten of MEMS-ECMs were plotted with no distinction. As a whole, these interval values show high correlation. However comparing the coefficient of determination (R^2) in Slow and Rapid conditions, it varies more widely in Rapid condition ($R^2 = 0.797$) than that in Slow ($R^2 = 0.99$). It is well known that the change in the pitch of breath results in the change in the heart rate. If one breathes slowly the heart rate goes down and vice versa which is so called respiratory arrhythmia (Ganong, 2003). Parasympathetic nervous system of the heart should be enhanced by slow breathing. It results in the enhancement of vascular sympathetic nervous system which leads to the constriction of small artery and muscle. In plain words, the forearm becomes stiff in slow condition. This can be a possible explanation of the high correlation between ECG and MEMS-ECM. This can be assumed as another example of that MEMS-ECM signal somehow represents the internal physical conditions.

CONCLUSION AND FUTURE WORKS

In this study, we developed a multiple human pulse wave sensing structure by interspacing MEMS-ECM sensors. It is successfully demonstrated that MEMS-ECM sensors are sensitive enough to detect human pulse wave which propagates over 10 m sec^{-1} in our body. Moreover, it is suggested that an internal physical condition in relation to an activity of sympathetic/parasympathetic nervous system might be estimated by comparing pulse signals derived by multiple MEMS-ECM sensors.

In the field of clinical medicine and health science, hemodynamic characteristics of the body provide us with useful and important information for maintaining our daily health. Moreover, such hemodynamic characteristics has been investigated in the field of ergonomics, human interface and other related engineering since it is known to have close relationship with the emotional and affective state of human (Ganong, 2003). Far more exploitation of the use of this micro device for the measurement of human cardiovascular system toward health care is expected.

ACKNOWLEDGMENT

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