High-sensitivity body-conducted sound sensor

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1. Introduction

We have developed a compact high-sensitivity sensor for body-conducted sounds such as heartbeats, lung sounds, blood-flow and gait sounds. The sounds are generated either inside or outside of the body, propagated through the body, and appear as weak vibrations of the body surface. The body-conducted sounds have many low-frequency components because the human body exhibits a strong low-pass filtering property [1].

Acoustic stethoscopes are commonly used by physicians to listen to heartbeats. One problem with acoustic stethoscopes is that the sound level is low. An electronic stethoscope surmounts this problem; a microphone installed in a stethoscope head senses air-pressure changes in the head cavity, then the sensed signal is amplified electronically. However, amplification of the signal sometimes generates artifacts and limits the bandwidth. A piezoelectric acceleration sensor has also been used to sense body-conducted sounds; its sensitivity, though, is not sufficient.

2. Sensor architecture

Our newly developed body-conducted sound sensor has an electret condenser microphone (ECM) with an exposed diaphragm that is covered with a soft polymer material so as to provide better acoustical impedance matching with the soft tissue of the skin. The sensor architecture is similar to that of non-audible murmur (NAM) microphone, which can sense very weak whispers inaudible to nearby listeners and even the speaker when it is placed on the skin at the lower part of the mastoid process, i.e. high on the neck behind the ear. [2].

Figure 1 depicts the architecture of the newly developed body-conducted sound sensor. The ECM mounted on a printed-circuit board is installed in a cylinder- or cone-shaped concave metal housing. The concave is filled with urethane elastomer, which adheres to skin. The vibration of the skin is transmitted to the exposed diaphragm of the ECM via the urethane elastomer.

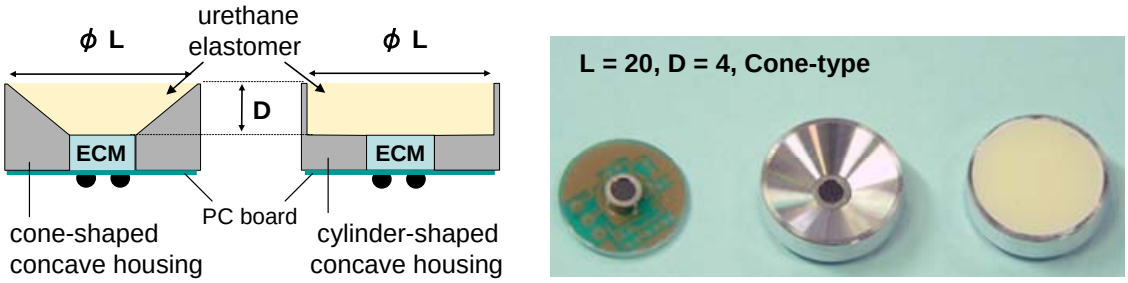

Figure 1: Structures and photographs of body-conducted sound sensor.

Key design changes from the NAM microphones [2] are (1) fixing of the ECM position, (2) use of a metal housing, (3) use of a cylinder- or cone-shaped concave housing, and (4) installation of a pre-amplifier circuit. Fixing of the ECM and using a concave housing contributed to improving the sensor sensitivity. The use of a metal housing contributed to reducing hum noise.

3. Sensor sensitivity

The sensitivities of body-conducted sound sensors were measured using an audio analyzer (3560C/3100; Brüel & Kjær), an accelerometer (NR-3211; Ono Sokki) that has a flat response of acceleration less than 10 kHz, a vibrator (4810; Brüel & Kjær) and a urethane elastomer cylinder of 75-mm diameter and 50-mm height, which simulates human soft tissues. The vibrations transmitted through the cylinder were subsequently sensed by the sensor and the accelerometer, and then mutually compared.

Figure 2 shows the pressure and acceleration sensitivity of body-conducted sound sensors that have a cone- (blue line) or cylinder-shaped (red line) concave housing of 20-mm diameter with 4-mm depth. The pressure sensitivity of the cone-housing sensor is above -55 dB (0 dB = 1 V/Pa) and that of the cylinder-housing sensor is above -70 dB. The acceleration sensitivity of the cone-housing sensor is above -15 dB (0 dB = 1 V/ms^2) below 300 Hz and that of the cylinder-housing sensor is above -20 dB. They are much higher than that of a commercially available piezoelectric-accelerator-based sensor (S-17; Promo).

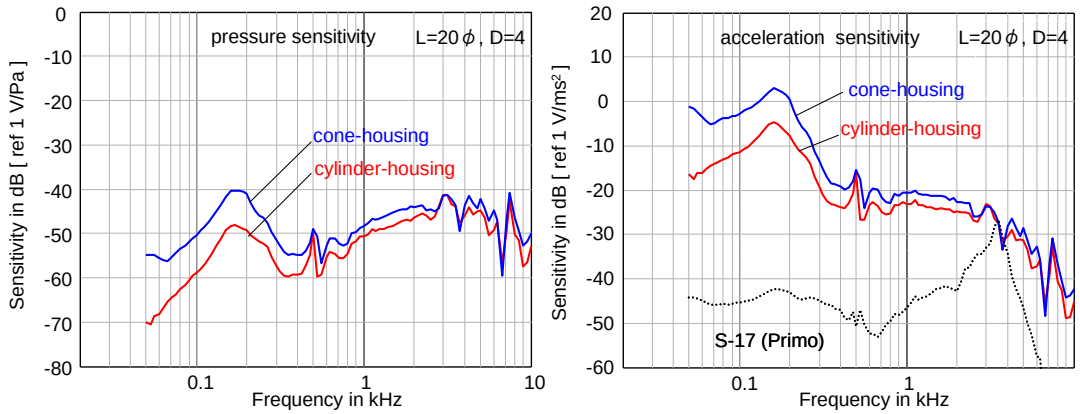

Figure 2: Pressure and acceleration sensitivity of body-conducted sound sensors.

4. New soft polymer material for sensor

Urethane elastomer (EXSEAL Corp., Japan) is used as a soft polymer material because it reversibly adheres to skin. We further investigated two polymer materials that can possess reversible adhesive power to skin.

One material investigated was a nano-fiber of segmented polyurethane fabricated by an electrospinning method. The nano-fabrication should promote interaction between the polyurethane and human skin because of the increased surface area. The nano-fiber film could cover the whole ECM area; it was found, however, that the strength of adhesion on skin was insufficient compared with urethane elastomer.

Another material tested was a new class of adhesive gel based on *N*-[2-(3,4-dihydroxyphenyl)-ethyl]-2-methyl-acrylamide (dopamine methacrylamide, DMA). The use of DMA was inspired by adhesive proteins (APs) that the blue mussel, *Mytilus edulis*, biologically synthesizes. The APs contain significant amounts of L-3,4-dihydroxy phenylalanine (DOPA). APs are believed to show adhesive and cohesive characteristics due to DOPA-mediated intermolecular interaction.

DMA was prepared according to the previously reported protocol by H. Lee *et al*. [3]. The chemical structure of DMA was confirmed by ^{1}H- and ^{13}C-nuclear magnetic resonance (NMR) spectroscopy. The obtained DMA (0.68 g, 3.07 mmol) and 2-hydroxyethylmethacrylate (HEMA) (0.4 g, 3.07 mmol) were co-polymerized by a conventional radical polymerization method with *N,N*'-azobisisobuthylonitrile (AIBN) (42 mg) in dimethylacetamide (DMF) (9.5 ml) at 60°C overnight (Figure 3). The crude product was washed with ether three times to obtain the co-polymer [poly(DMA-*co*-HEMA)].

The poly(DMA-*co*-HEMA) (0.5 g) was mixed with dicyclohexylmethane-4, 4'-diisocyanate (0.25 g) in an ECM, and then it was settled at room temperature overnight. As a result, gel-like resin was obtained as shown in Figure 4. This was

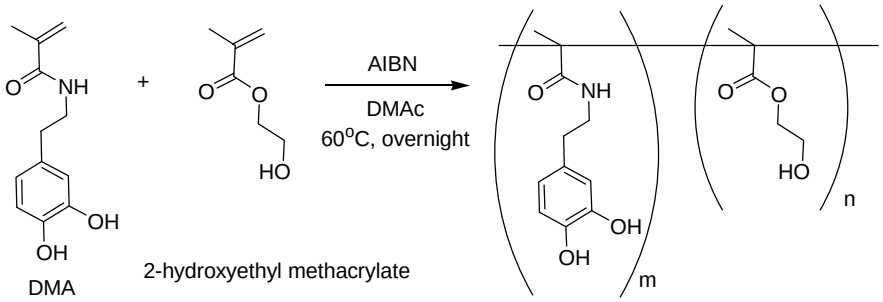

Figure 3: Radial polymerization of dopamine methacrylamide and HEMA.

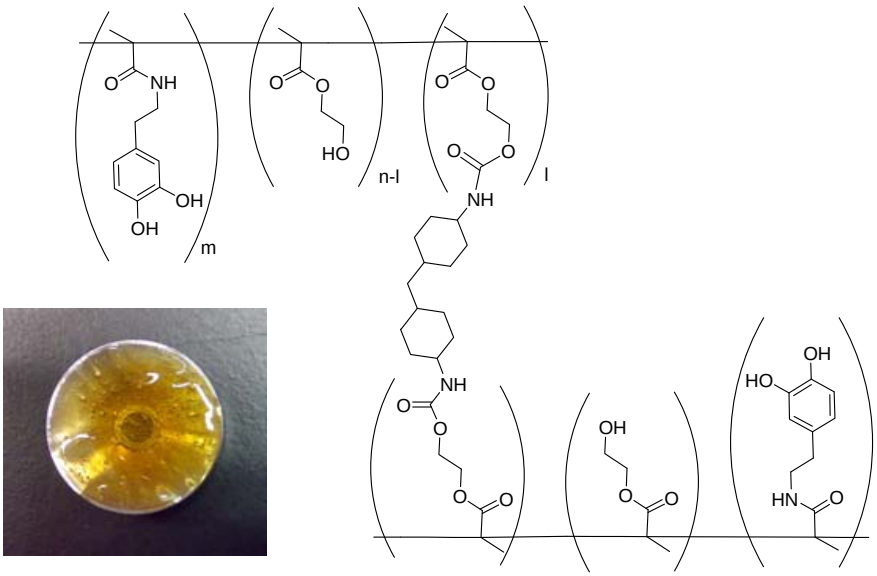

Figure 4: Proposed structure of gel obtained by crosslinking reaction and poly(DMA-*co*-HEMA)-crosslinked gel-deposited body-conducted sound sensor.

due to a crosslinking reaction between hydroxyl groups of the poly(DMA-*co*-HEMA) and diisocyanate group (Figure 4).

When the poly(DMA-*co*-HEMA) gel-deposited sensor was attached onto the back of a hand and the hand was turned upside down, the sensor remained attached for at least for 30 min. In contrast, in the same situation, the urethane elastomer-deposited sensor detached from the hand after 4 min. Thus, the adhesion strength of the poly(DMA-*co*-HEMA) gel was much greater than that of the urethane elastomer. Although the poly(DMA-*co*-HEMA) gel-deposited sensor revealed a strong adhesive property, the adhesive strength decreased with time. Improving the durability is a future issue.

5. Recording body-conducted sounds

Using the sensor, we could record various kinds of body-conducted sounds such as cardiac, blood-flow, vesicular, bowel peristalsis sounds and muscle murmur. Figure 5 shows typical waveforms of cardiac sounds sensed at the chest (left) and finger pulsation sounds sensed at the index finger (right) with the sensor.

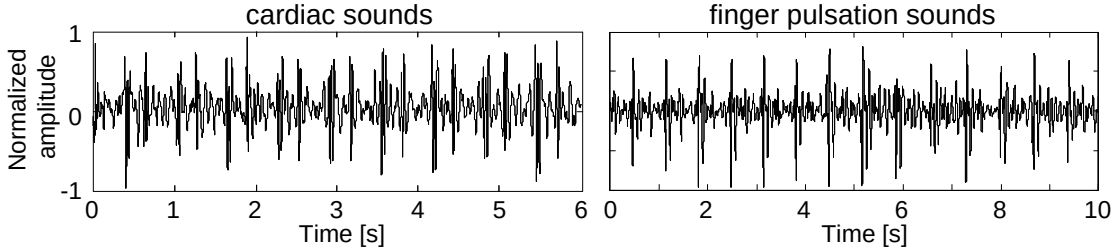

Figure 5: Examples of body-conducted sounds' waveforms recorded with sensor.

6. Conclusion

A compact high-sensitivity body-conducted sound sensor was developed. Urethane elastomer was used as a soft polymer material for the sensor because it reversibly adheres to the skin. A poly(DMA-*co*-HEMA) gel revealed a strong adhesive property but its durability was poor. Various kinds of body-conducted sounds could be recorded with the sensor, suggesting that it can be used as an input device for a vital-signs monitoring system as well as a life-log system.

Acknowledgements:

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References

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