IADIS International Journal on WWW/Internet
Vol. 11, No. 3, pp. 116-125
ISSN: 1645-7641

MULTIPLE PULSE WAVE MEASUREMENT TOWARD ESTIMATING CONDITION OF HUMAN ARTERIES

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ABSTRACT

The human pulse wave conveys clinically significant information related to the symptoms of cardiovascular diseases. The use of a photoplethysmograph (PPG) is a conventional means of detecting the human pulse. However, the locations where a PPG can be applied are quite limited, such as an ear lobe or the fingertip, thus limiting the application of the PPG for healthcare use. In this study, we propose a new pulse-sensing apparatus that employs multiple silicon microphone sensors, which provide physiologically rich information regarding the body, such as the condition of the arteries and activity of the autonomic nervous system. The silicon microphone is an electret condenser microphone fabricated using a microelectromechanical system (MEMS-ECM). Because it is not a mere microphone, but rather, a pressure sensor that possesses a wide range of frequency response, it can detect the human pulse wave, which has a dominant frequency of 1.4 Hz. By installing MEMS-ECMs on the surface of the skin surrounding the upper arm, we successfully demonstrated that these semiconductor sensors are sensitive enough to determine the rate of pulse propagation, which represents the stiffness of the arteries and activity of the autonomic nervous system.

KEYWORDS

Pulse wave, Silicon microphone, Artery, Autonomous System Activity, Healthcare device.

1. INTRODUCTION

The human pulse wave is a pressure wave generated by the mechanical constriction and relaxation of the heart. It propagates through the blood vessels at a maximum rate of 10 m/s (Ganong, 2003). Down through the ages, and particularly in oriental medicine, the human pulse has been used as a means of diagnosing the symptoms of cardiovascular diseases. Modern medicine has now scientifically demonstrated that there is a close relationship between human pulse waveforms and the symptoms of cardiovascular diseases. Sano et al. (1985) reported that the human pulse wave in an accelerated form (secondary differentiated pulse wave signal) of patients who had experienced or displayed a symptom of cardiovascular disease had a composition that is distinct from that of the healthy population (Sano, 1985). Moreover, the pulse wave gives us a variety of physiological information that is conducive to improved healthcare, even in a non-clinical situation. Chen et al. (2000), for example, proposed a continuous blood pressure measurement device by referring to the pulse waveform and its latency (Chen, 2000). Suzuki et al. (2010) proposed a method of cuffless blood pressure estimation via pulse wave analysis that makes use of a soft-computing technique (Suzuki, 2010). The beat-to-beat interval of the pulse enables us to determine the variability of the heart rate, which represents the activation or balance of the sympathetic/parasympathetic nervous system (Pomeranz, 1985). In this regard, a ‘smart’ vehicle has been proposed that estimates the driver’s heart rate variability, enabling the vehicle to presume the driver’s mental and physical condition (Healey, 2005).

Despite these advances, the method used for detecting the human pulse wave has not been developed to such a sophisticated degree in modern times. Currently, the most common technique used to identify the human pulse wave is photoplethysmography (PPG). PPG is an optical method in which one observes changes in the absorption rate of infrared light (normally 780 nm), which is linearly associated with the haemoglobin content of the blood flow. At present, PPG is the most reliable and even cost-effective method for pulse detection. However, PPG has a limitation. Because the depth of the infrared light transmission within the body is 2–4 mm, the locations where PPG can be applied are quite limited, such as an ear lobe or the fingertip. Moreover, because a PPG can perform detection only at such peripheral sites of the body, it does not provide information about the arteries themselves, which would be clinically significant information, because it detects only peripheral vascular information. For this reason, we propose a new apparatus to detect the human pulse wave, which employs multiple silicon microphone devices.

2. PULSE DETECTION BY ELECTRET CONDENSER MICROPHONE

2.1 MEMS-ECM, a Silicon Microphone

The silicon microphone introduced in this study is an electret condenser microphone fabricated using a microelectromechanical system (hereafter denoted as MEMS-ECM), as shown in Fig. 1. A MEMS-ECM is a small microphone that is assembled by semiconductor production processing. Because it has a great advantage over other microphones or ECMs in terms of size and quality, MEMS-ECMs are widely used as a microphone that is mounted in cell phones and smartphones worldwide. The MEMS-ECM consists of an ECM in which an electro-charged back-plate and a metal diaphragm form a micro-condenser, and a CMOS chip in which a signal amplifier, buffer, and electro charge pump are integrated in a small chip.

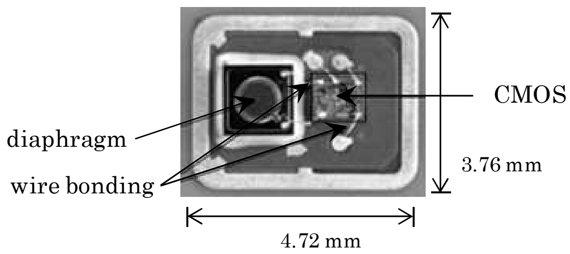

Figure 1. MEMS-ECM, a silicon microphone.

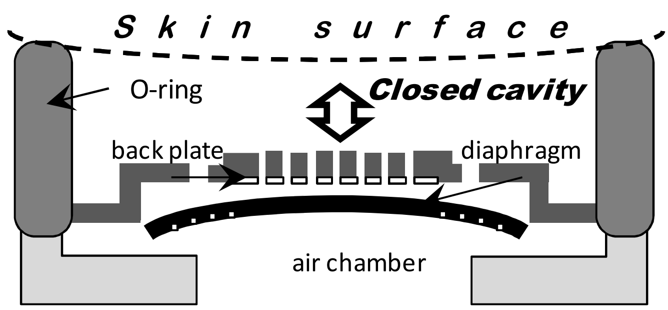

Figure 2. Closed cavity formed between MEMS-ECM and skin surface.

2.2 Pulse Detection by MEMS-ECM

The MEMS-ECM is a silicon condenser microphone chip. In other words, it is a pressure sensor that offers high quality and performance. In addition, the frequency response of the MEMS-ECM is theoretically constant, owing to its so-called stiffness-controlled structure. Although a reduction in sensitivity in a lower frequency range can be produced by the CMOS chip, which has an amplifier with high-input impedance, it is possible to detect human pulse signals from the skin surface via the vibration of the skin, as generated by the propagation of the pulse wave. We previously reported that the frequency response of the MEMS-ECM was equivalent to the differentiation circuit in a range lower than 100 Hz, which is a typical resistor–capacitor circuit (RC circuit) that has a sensitivity reduction of -20 dB/dec (Nomura, 2011). The dominant frequency of the human pulse is around 1.4 Hz. This means that the MEMS-ECM can detect the human pulse wave as a difference in air pressure. However, it should be noted that owing to the property of the RC circuit, the obtained signals are in the form of velocity.

We developed the MEMS-ECM device with a rubber o-ring attached to it, so that a closed cavity was formed between the skin and the diaphragm of the sensor, as shown in Fig. 2. With this closed cavity, the mechanical vibration of the skin that is produced by the human pulse can be transmitted through the MEMS-ECM diaphragm, so it is converted into an electrical signal. Fig. 3 shows pulse waves detected by an MEMS-ECM sensor (SPM0408HD5, Knowles Acoustics, LLC., USA/Japan; the specifications are listed in Table 1.), which is placed at the radial artery near the wrist. As just described, the raw signal (Fig. 3(a)) obtained by the MEMS-ECM provides the pulse wave in terms of velocity, owing to the frequency characteristic of this microchip. Therefore, the ordinary human pulse wave is obtained via integration of the raw signal (Fig. 3(b)). This pulse wave detected by the MEMS-ECM is quite similar to that obtained by direct measurement using arterial catheterisation at the brachial site (Ganong, 2003). The acceleration pulse, however, which provides clinically significant information (Sano, 1985), is obtained by differentiation of the raw signal (Fig. 3(c)).

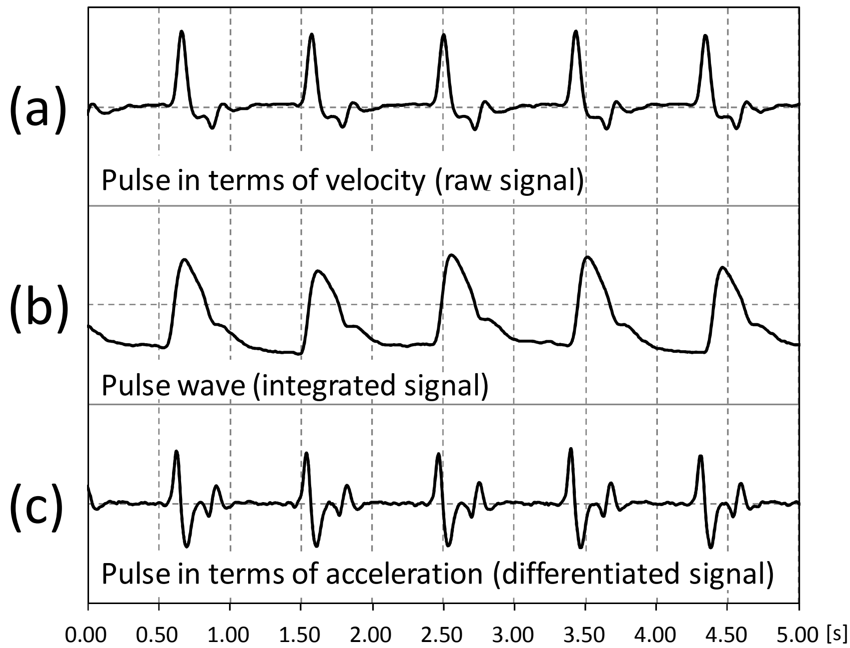

Figure 3. Pulse waves obtained by MEMS-ECM (a) in terms of velocity (raw signal), (b) pulse wave (integrated raw signal), and (c) in terms of acceleration (differentiated raw signal).

Table 1. Specifications of MEMS-ECM

Sensitivity	-22 dB @1 kHz (0 dB = 1 V/Pa)
S/N	59 dB @1 kHz (0 dB = 1 V/Pa)
Supply Voltage	1.5–3.6 V
Height	1.250 mm
Length	4.720 mm
Width	3.760 mm
Acoustic Port	0.838 mm

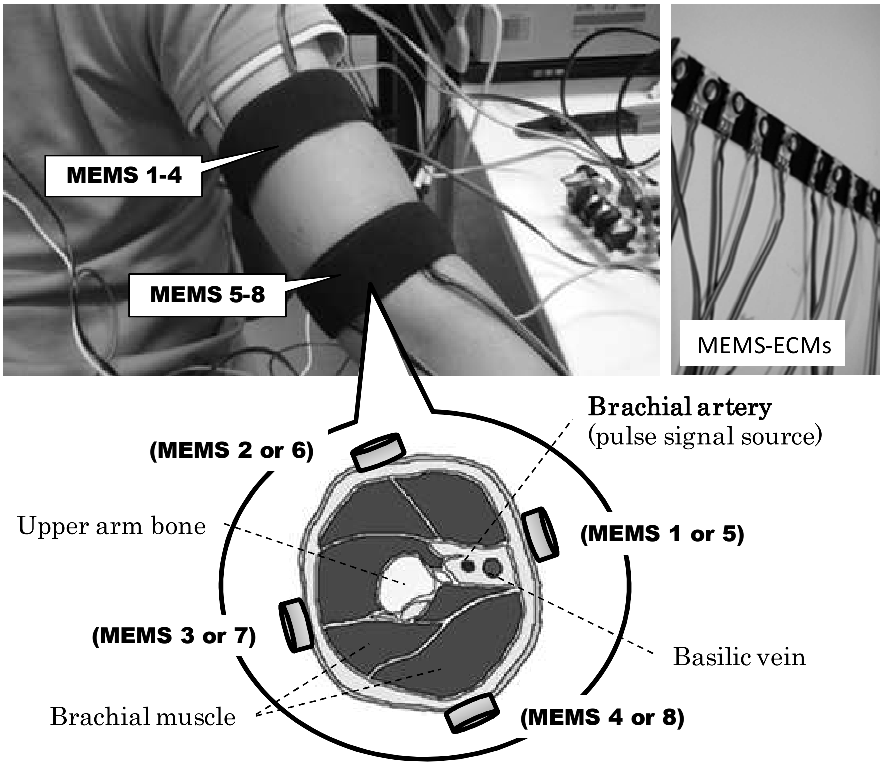

Figure 4. Experimental setting of the multiple MEMS-ECM pulse detection.

3. PULSE DETECTION BY MULTIPLE MEMS-ECMS

3.1 Experimental Settings

We have developed a new human-pulse measurement apparatus that employs multiple MEMS-ECM sensors. As shown in Fig. 4, eight MEMS-ECMs were placed at equidistant intervals on the surface of the forearm: four MEMS-ECMs (denoted as MEMS 1 to 4) were placed with an interspacing of 90° from each other in the cross-sectional direction, and the other four (denoted as MEMS 5 to 8) were placed in the same manner, but at lower part of the forearm. Each of the four MEMS-ECMs was covered by a Velcro strap that fixed each of to its assigned location.

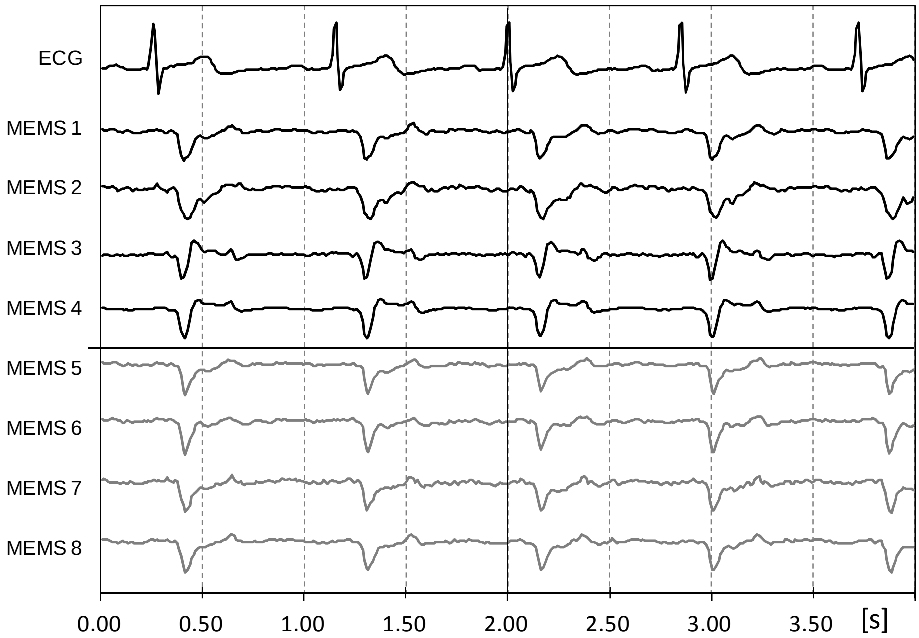

Figure 5. Pulse signals obtained by multiple MEMS-ECMs and ECG.

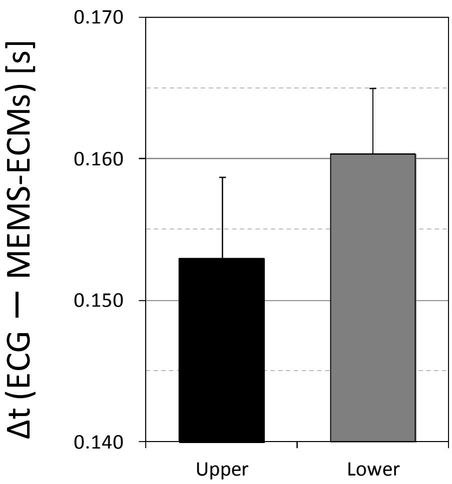

Figure 6. Latencies in the peak times of MEMS-ECMs on the upper and lower forearm, respectively.

The analogue signal acquired by each MEMS-ECM was transferred and digitised by a versatile bio-signal amplifier and recorder system (BIOPAC MP150 system, BIOPAC Systems Inc.). The signal sampling of eight MEMS-ECMs was performed synchronously at a resolution of 16 bits and at a rate of 4000 Hz (sampling rate). Proprietary software that was developed for the bio-signal amplifier (AcqKnowledge 3.9., BIOPAC Systems Inc.) was used for further analysis.

3.2 Latencies in the Peak Time and Pulse Wave Velocity (PWV)

Fig. 5 shows typical signals obtained by multiple MEMS-ECM sensors, and by a heartbeat signal (Electroencephalogram: ECG) for reference. It was observed that there was a latency in the peak time, at around 150–160 ms, between the ECG's (the so-called R-wave) and the signals from the MEMS-ECMs. This latency represents the propagation time of the human pulse wave from the heart to the site where the MEMS-ECMs were placed. Although there is not a marked difference between the peak times of the MEMS-ECMs, there are nonetheless slight but significant time differences ($p < 0.001$), averaging around 7 ms, between MEMS 1–4, which were placed on the upper part of the forearm, and MEMS 5–8, which were placed on the lower part, as shown in Fig. 6. Because the distance between the locations of MEMS 1–4 and those of MEMS 5–8 is around 5 cm, the propagation time of the pulse, which can be considered to be equivalent to the so-called pulse wave velocity (PWV), would be around 7 m/s.

The PWV can be used as an indicator of arterial stiffness in a clinical situation. Conventionally, it is measured by the time difference between the pressure wave at the heart and at the ankles, so it is not necessary for it to be equivalent to the actual propagation time of the pulse, but rather, to the average propagation time in the entire body. In addition, substantial facilities are required to check the pulses on the different limbs, which must be done with the help of experts. In this regard, our proposed method makes it quite easy, even in a domestic situation, to measure the pulse wave velocity. This advantage is attributed to the high and uniform quality of the MEMS-ECM, which is achieved by semiconductor production processing.

3.3 Autonomic Nervous System Activity and Changes in Arterial Characteristics as Estimated by Multiple MEMS-ECM Signals

In this next section, for the purpose of comparing pulse signals under different modes of autonomic nervous system activity, pulse signals were measured using the same experimental setting as that shown in Fig. 4, with the subjects' breathing controlled at three rates: (1) normal (hereafter denoted as a 'Normal' condition), (2) slow ('Slow'), and (3) fast ('Fast').

Fig. 7 shows the correlativity between the beat-to-beat intervals of the heartbeat (R-R interval) and the corresponding intervals of the signals of the MEMS-ECMs. It should be noted that the value for each of the MEMS-ECMs was plotted without distinguishing one from another. On the whole, these interval values show a high degree of correlation. However, if we compare the coefficient of determination (R^2) for the Normal, Slow, and Fast conditions, we find that it varies more widely in the Fast condition ($R^2 = 0.73$) than it does in the Normal ($R^2 = 0.96$) and Slow ($R^2 = 0.99$) conditions. It is well known that a change in the rate of breathing results in a change in the heart rate and its variability. As one breathes more slowly, the heart rate decreases, and vice versa, in a phenomenon known as respiratory arrhythmia (Ganong, 2003). The parasympathetic nervous system of the heart is enhanced by slow breathing. This results in the enhancement of the vascular sympathetic nervous system, which leads to the constriction of small arteries. In short, the forearm becomes stiffer in the Slow condition. This implies that there would be less of a dumping effect of the pulse wave within the forearm, and thus the pulse form, especially the peak form, is well preserved during the propagation. This offers a possible explanation for the high correlation between the ECG and MEMS-ECM. In the Fast condition the contrary may be true, as the small arteries might become enlarged to compensate for the increased blood flow that results from the enhancement of cardiac activity. This would make the process of pulse propagation more complicated, introducing a variety of factors such as the elasticity of tissue and the architecture of the arteries. This, then, might be the reason for the relatively lower coefficient in the Fast condition. In any event, the pulse signal obtained by multiple MEMS-ECMs changes sensitively according to the physiological conditions of the body.

Fig. 8 shows the pulse wave propagation speed as determined by the distance (5 cm) between the upper part and the lower part of the forearm, divided by the difference in the latency. The mean velocity of around 6–7 m/s is quite consistent with the PWV obtained by direct measurement using arterial catheterisation (Ganong, 2003). This confirms the high quality and sensitivity of the MEMS-ECM as a pulse sensor. However, there is still a difference in the pulse propagation speed among the three breathing conditions. The pulse propagation speed is lower in the Fast condition. This is understandable, because faster breathing induces an enhancement of the heart's sympathetic nervous system activity, which enlarges the arteries and results in slower pulse propagation. The relatively slower pulse propagation in the Slow condition as compared with the Normal condition might be attributed to a mere reduction in the contraction/relaxation activity of the heart.

In summary, the pulse measurement obtained by multiple MEMS-ECMs is sensitive enough to determine the pulse wave propagation time as well as its modulation, which reflect both the physical property of the arteries embedded in the forearm and the enhancement of the autonomous nervous system.

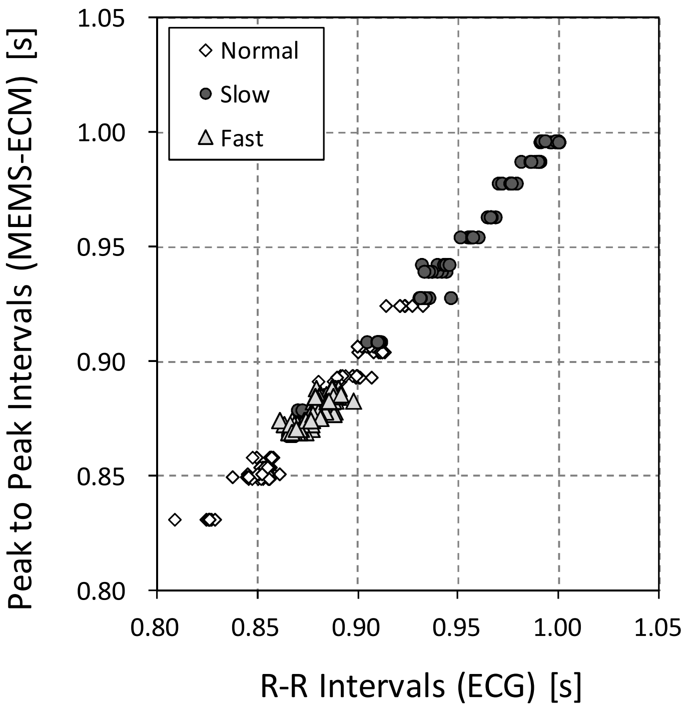

Figure 7. Beat-to-beat intervals of the heart beat and that of corresponding intervals of the signals of the MEMS-ECMs.

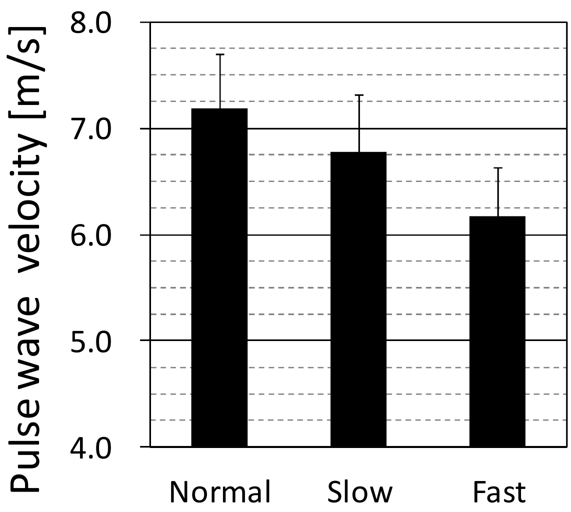

Figure 8. Pulse propagation rate in Normal, Slow, and Fast conditions.

4. CONCLUSION

In this study, we developed a multiple human-pulse sensing structure, using MEMS-ECM sensors as a new apparatus that represents a step toward estimating the condition of human arteries and autonomic nervous system activity. It was successfully demonstrated that MEMS-ECM sensors are sensitive enough to (1) determine the rate of pulse propagation only within a limited area and (2) capture the physiological condition of an artery that is closely controlled by autonomic nervous system activity.

In the field of clinical medicine and health science, the haemodynamic characteristics of the body provide useful and important information for maintaining our daily health. Moreover, such haemodynamic characteristics has been investigated in ergonomics, human interface, and other related engineering fields, because it is known to have a close relationship with the emotional and affective states of humans (Healey, 2005; Nomura, 2011; Williams, 1986). Because our proposed apparatus is a small digital device that is easy to handle, cost effective, and quite conducive to networking, it can be implemented as a domestic healthcare device in our daily life. We can also expect that the use of this micro-device for the measurement of the human cardiovascular system will be profitably expanded in many other health care applications.

ACKNOWLEDGEMENT

The MEMS-ECM chips used in this study were provided by Knowles Acoustics, LLC., USA/Japan. This study was supported in part by the Adaptable and Seamless Technology Transfer Program through Target-driven R&D, of the Japan Science and Technology Agency.

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