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Original Article

A new flexible pressure sensor contributes to the early diagnosis of acute compartment syndrome

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Abstract: Acute compartment syndrome (ACS) is a surgical emergency, caused by the sharp increase of interstitial pressure within a closed osteofascial compartment, which can impair local circulation and functions. A non-invasive sensor is needed of satisfactory sensitivity to continuously monitor the alterations of the ACS pressure, which could be used as a supplementary means in the early diagnosis of ACS. A prepared "pasting-type" flexible pressure sensor was used to establish an extracorporeal pig-skin model with a soft-tissue expander device to simulate compartment syndrome conditions. An acrylic panel was inserted into the pig skin, allowing the soft-tissue expander to expand in one direction, which is similar to the movements of a patient's bones in real life. The touch spot of the flexible pressure sensor was attached to the rind by medical tape, to record the internal and external pressure data. Relationships between the internal and external pressures at different thickness (0.87 mm, 3.53 mm and 3.97 mm), as well as that of the 3.97 mm thickness under various initial internal pressures (0.5 mmHg, 25 mmHg and 44 mmHg) were measured. Significant differences were observed in the range of internal pressures at various pig-skin thickness. After adding the acrylic panel, the measured ranges were significantly increased, with the lowest measurable internal pressure being 5 mmHg. Moreover, alterations in external pressure were also greater than in models without acrylic panels. The external pressure measured by the sensor was able to reflect an increase in intra-organizational pressure. This may be a new non-invasive and sustainable method for early diagnosis of ACS.

Keywords: Acute compartment syndrome, flexible pressure sensor, external pressure, internal pressure

Introduction

Acute compartment syndrome (ACS) is a surgical emergency, caused by the sharp increase of interstitial pressure within a closed osteofascial compartment, which can impair local circulation and functions. The venous pressure and the intracompartment pressure (ICP) in the limbs both increase, resulting in a reduced arteriovenous pressure gradient and insufficient local blood perfusion that causes an inability to meet the needs of tissue metabolism, which can further lead to a series of severe ischemic symptoms [1-4]. With respect to the measurement of intrafascial pressure, the direct measurement method developed by Whitesides in 1975 is still widely used today. This method requires the insertion of a no. 18 needle, connected to a mercury sphygmomanometer, into the limb to measure the intrafascial pressure. Values between 10 and 30 mmHg are considered as up-regulated levels, and those higher than 30 mmHg as significantly increased levels. Despite the ease of operation, the method has rather poor precision, since the needle can be blocked by soft tissues [5]. Therefore, a variety of modified methods were developed, including the modified Whitesides method developed by Mubarak et al. (1976). They used catheters with a core, which inevitably would be blocked by a blood clot, and the needle could be left behind [6]. Rorabeck et al. (1981) further improved the method by using a fractured catheter, which not only solved the problem of blockage by blood clots and soft tissues, but also improved the measurement precision [7]. However, Mubarak (1983) suggested to deform the fractured catheter, which could affect precision [8]. Later, Awbrey et al. (1988) further improved the needle by adding a side hole to improve the sensitivity of the measurement equipment, and thereby simultaneous

measurement of multiple osteofascial chambers was achieved, which promoted the wide application of this method [9]. More recently, Moed et al. (1993) and Willy et al. (1999) connected the sensor to the main measurement engine to directly display the intrafascial pressure [10, 11].

Regarding the indirect test methods, Gershuni et al. (1982) utilized the B-type ultrasonic detector as the diagnostic technique for compartment syndrome, based on the volume-pressure correlation principle [12, 13]. Another researcher (1998) also adopted CT and MRI to observe the compartment area for the evaluation of intrafascial pressure [14]. Wiemann et al. [15] directly taped the ultrasonic transducer to the skin surface and continuously monitored the distance between the skin surface and the subcutaneous tissue. The impulse-type phase-locked loop, ultrasonic instrument could reflect ultrasonic waves and since the distance was considered to be linearly correlated to the pressure results, the measured results were compared with their own data to monitor the changes in the pressure. Although several methods for the detection of intrafascial pressure are available, they each have limits; the direct test methods may lead to the comorbidities of bleeding and infection, while the indirect methods may not be applicable in continuous observation. Moreover, the exact pressure levels cannot be obtained by indirect test methods, which further limits its clinical application.

Flexible electronics, also known as plastic electronics, printed electronics, organic electronics and polymer electronics, is a general term for a large group of technologies that are still in their infancy and are being developed vigorously [16-19]. In this study, a prepared "pasting-type" flexible pressure sensor (**Figure 1**) was used to measure the external pressure of the affected part in pig-skin models with compartment syndrome.

The prepared flexible pressure sensor was a resistance-type pressure sensor. The micro-nano structure direct writing technique was adopted to prepare the response units on the flexible foundation with silver paste, which was then connected with wires and encapsulated by PDMS. Compared with traditional preparation methods, such as evaporation, and photoetching, the above-described technique is more environment-friendly, and has the advantages of wide application, simple processes, low cost, and possible mass production.

In the present study, we established an extracorporeal pig-skin model with a soft-tissue expander device to simulate compartment syndrome conditions. The external and internal pressures, as well as the relationship between these pressures at different thickness (3.53 mm and 3.97 mm) were measured by the touch spot of the flexible pressure sensor on the pig skin. The results suggested that the external and internal pressure was positively correlated, and that the external pressure measured by the flexible pressure sensor can reflect changes in the internal pressure. It is necessary to discover a non-invasive type of sensor of satisfactory sensitivity to continuously monitor pressure alterations in ACS, as a supplementary means in the early diagnosis of ACS.

Methods

Preparation of the flexible pressure sensor

In this study, a prepared "pasting-type" flexible pressure sensor (**Figure 1**) was used to measure the external pressure of the affected part in the pig-skin model with compartment syndrome. The response area was 4×4 mm^2, and PDMS was used as encapsulating material, which added the promising features of water resistance and biocompatibility. The micro-nano structure direct writing technique was used to prepare the response units on the flexible foundation with silver paste, which was then connected with wires and encapsulated by PDMS.

Flexible electronic sensor and flexible printed circuit board

The flexible printed circuit (FPC) board is highly reliable and flexible, and based on polyimide or polyester film. The circuit board has the characteristics of being lightweight, thin and outstanding in bending performance, which makes it suitable for wearable devices (**Figure 1B**). In this study, the FPC board was adopted to conduct the pressure signal reading and serve as a transmission circuit, and was combined with the flexible pressure sensor to form a "band-aid type" flexible pressure sensor terminal node. The touch spot of the flexible pressure sensor

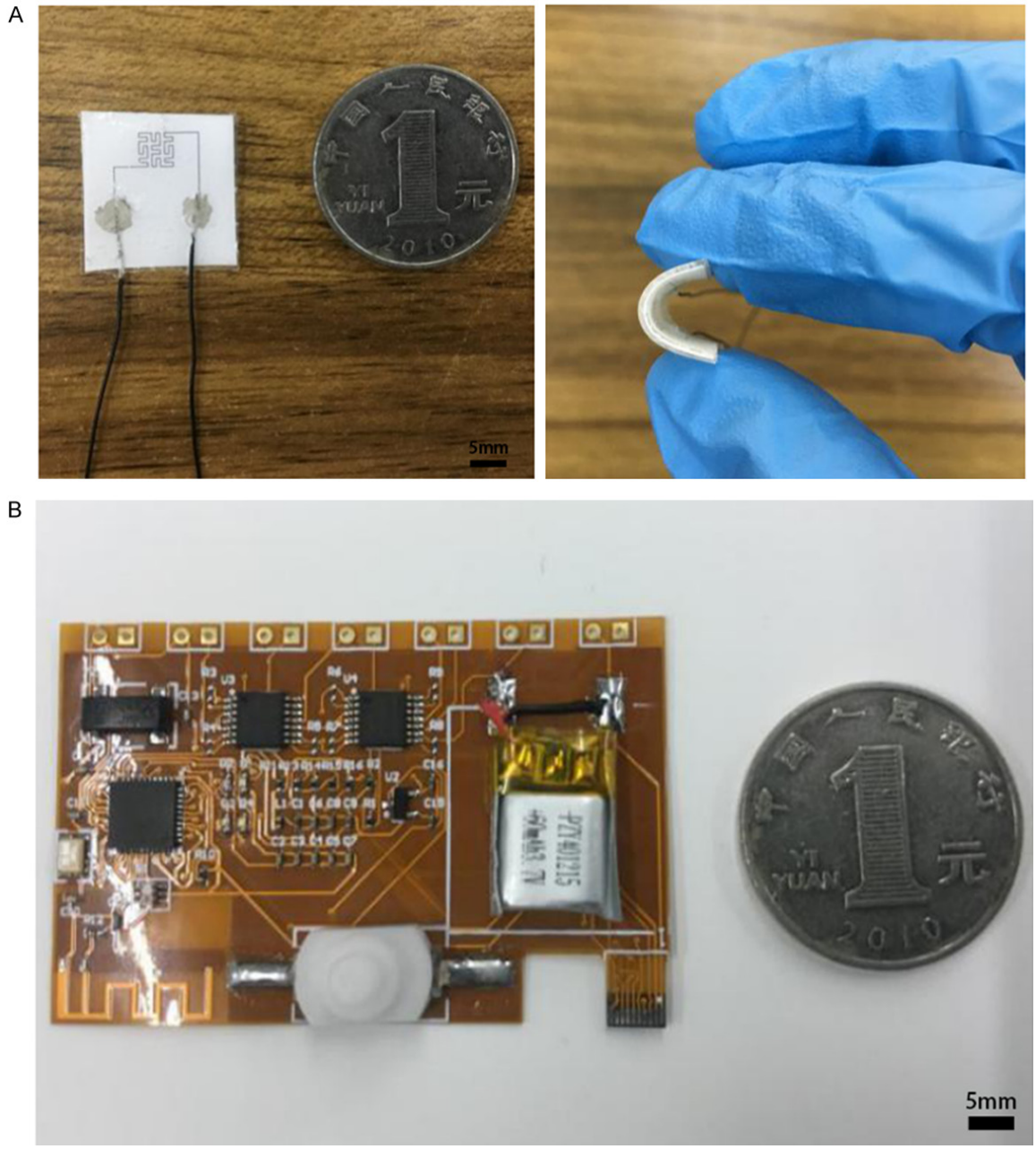

Figure 1. (A) flexible electronic sensor and (B) flexible printed circuit board.

was attached to the rind by medical tape, to record internal and external pressure data.

Preparation of extracorporeal pigskin model with soft-tissue expander device

The extracorporeal pig-skin model with soft-tissue expander device was established to simulate the condition of osteofascial compartment syndrome (**Figure 2A** and **2B**). The soft-tissue expander device was placed onto pig skins of different thickness (3.53 mm and 3.97 mm), which were sewn together into pouches, as shown in **Figure 2**. An acrylic plate was also inserted into the pig skin to allow the soft tissue expander to expand in only one direction, simulating the presence of human bones. The touch spots of the flexible pressure sensor were attached to the pig skin by medical adhesive tape, to measure the internal and external pressure at different thickness and under various internal pressures at different time points.

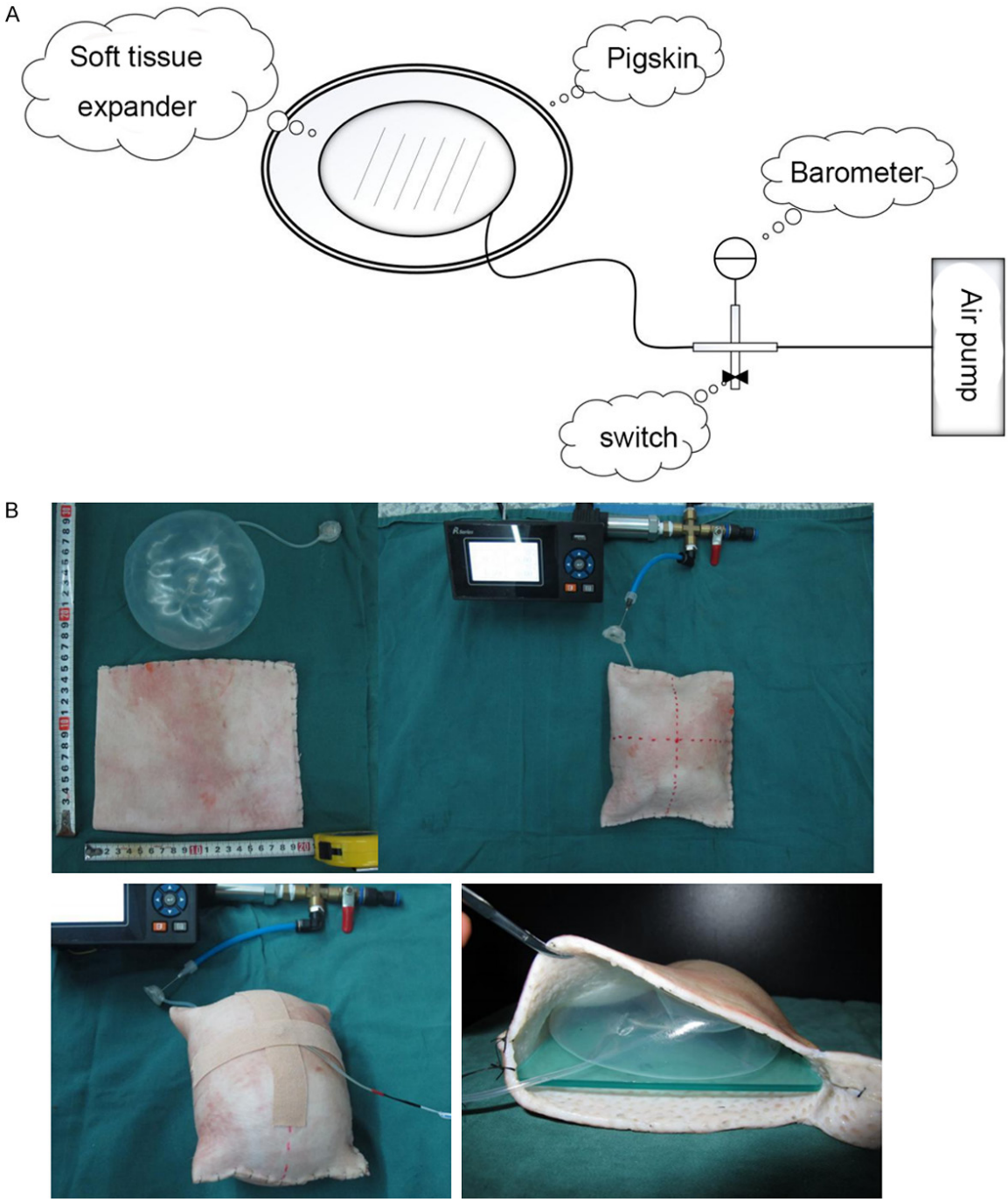

Figure 2. A and B. Establishment of an extracorporeal pig-skin model with soft tissue expander device to simulate compartment syndrome conditions.

Statistical analysis

All experiments were repeated three times independently and data are were presented as mean ± standard deviation. Analysis was performed using SPSS Version 13.0. Differences were compared by t-tests or one-way analyses of variance. $P < 0.05$ was considered significant.

Results

Effect of pig skin thickness on the relationship between internal and external pressure

Figure 3 represents the relationship between internal and external pressure at various thicknesses. Significant differences were observed in the range of internal pressures at various

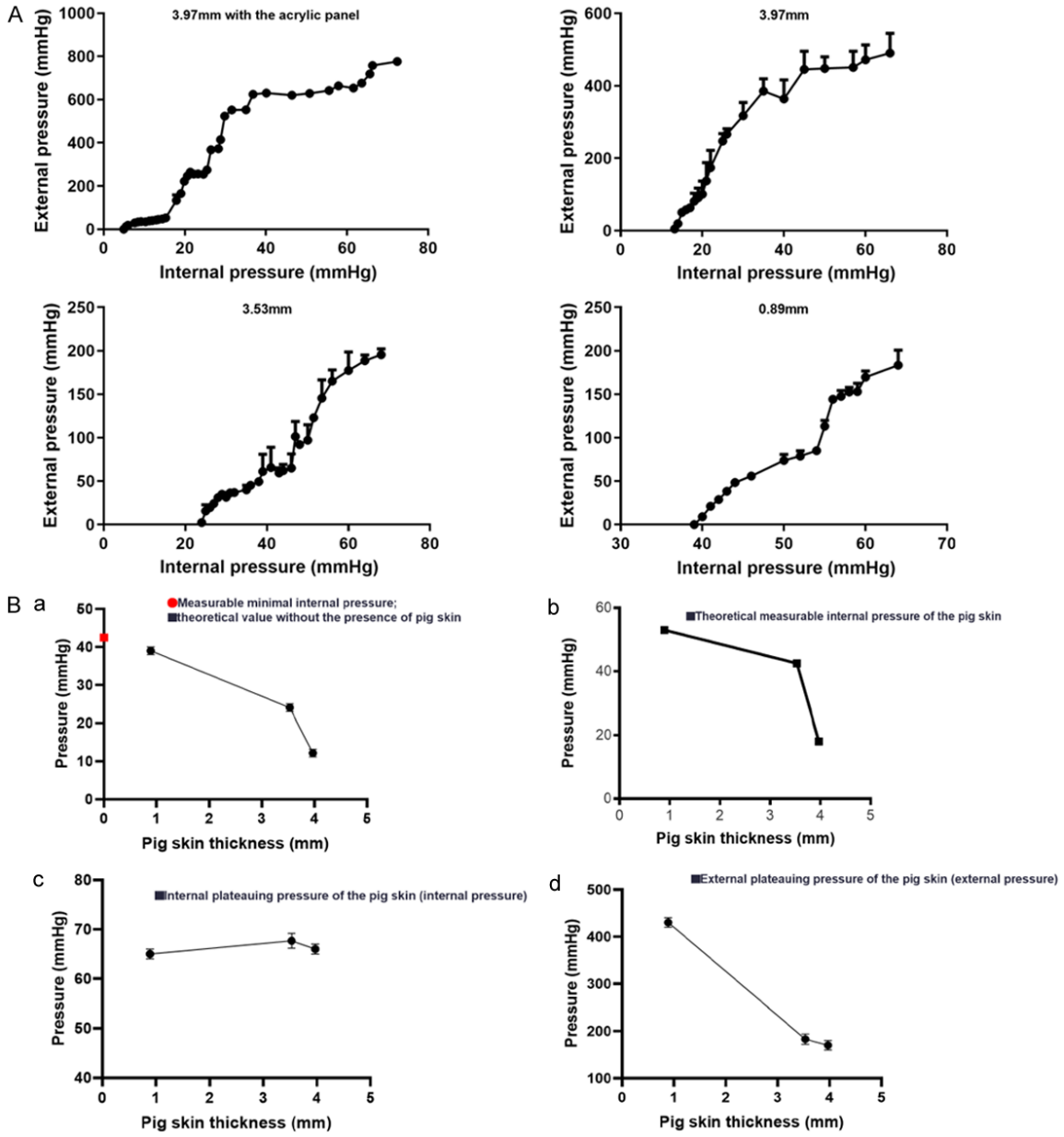

Figure 3. A. Relationship between internal and external pressure at various thicknesses reflected by the pig-skin model with soft-tissue expander device; B. a. The measurable minimal internal pressure detected by the sensor at various pig skin thicknesses; b. The theoretical measurable minimal internal pressure detected by the sensor without the presence of the soft tissue expander device; c. The measurable maximal plateauing internal pressure detected by the sensor (internal pressure) at various pig skin thicknesses; d. The measurable maximal plateauing external pressure detected by the sensor (external pressure) at various pig skin thicknesses. Results are expressed as mean ± SD of three individual experiments performed in triplicate for each condition.

pig-skin thicknesses. Under the initial internal pressure of approximately 0 mmHg, the lowest internal pressure at the skin thickness of 3.97 mm, was about 13 mmHg. The measured range was significantly increased compared with that of the 3.53 mm thick skin, where the lowest measured internal pressure was 23 mmHg.

As shown in **Figure 3**, there were two distinct plateauing phases in each external pressure-internal pressure curve, which was speculated to be related to model design. The alteration of the external and internal pressure included four phases. At the beginning, the external pressure sharply increased along with the expan-

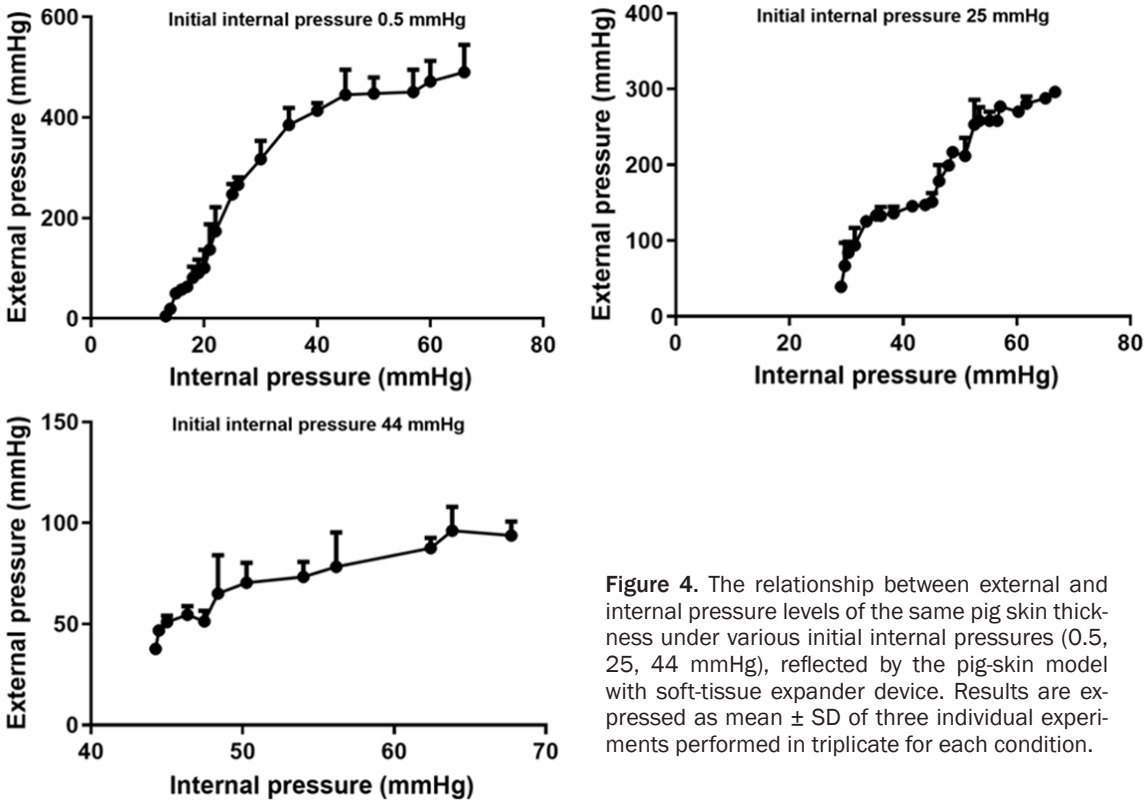

Figure 4. The relationship between external and internal pressure levels of the same pig skin thickness under various initial internal pressures (0.5, 25, 44 mmHg), reflected by the pig-skin model with soft-tissue expander device. Results are expressed as mean ± SD of three individual experiments performed in triplicate for each condition.

sion of the soft tissue expander device. Subsequently, the pig skin limited the expansion and the external pressure approached the first plateauing level. Then, the pig skin started to expand along with the continuous increase of the internal pressure, which resulted in up-regulation of the external pressure. Finally, the pig skin achieved the limit of expansion, and the external pressure approached the second plateauing level. The trend in variation can also be confirmed by the measured values. During the first phase, at various pig skin thicknesses, the minimum internal pressure value that could be measured by the sensor, was the minimum internal pressure that could be measured by directly attaching the sensor to the soft tissue expander. After adding the acrylic panel, the measured range increased, with the lowest measurable internal pressure being 5 mmHg. Moreover, the alteration in the external pressure was also more significant compared with those in other groups (**Figure 3A** and **3B**).

Effect of initial internal pressure on the relationship between external and internal pressure

At the skin thickness of 3.97 mm, the measured ranges varied along with the initial internal pressure. In addition, the measured range of the external pressure also decreased with the internal pressure. With an internal pressure of 44 mmHg (6 kPa) and higher, no remarkable change was observed in the external pressure (**Figure 4**).

Discussion

The early diagnosis of ACS relies on measurement of the ICP. However, it has been suggested that the ICP is not evenly distributed within the compartment chamber, and single-point puncture measurement may fail to reflect the actual condition, while repeated puncture measurements at multiple sites in clinical practice to obtain more pressure data, cannot be realized. Moreover, single-point puncture measurements are prone to over- or underestimating of the pressure of the whole limb, since ACS patients always have multiple affected compartment chambers, which leads to erroneous clinical judgements. In addition, Matava et al. measured the ICP at different levels in the anterior fascial compartment of patients with tibial fractures and demonstrated that the highest pressure was found in the area less than 5 cm away from the fracture, which is a risky puncture site that could lead to open fractures and

comorbidities, such as bleeding and infection [20]. Although indirect test methods can achieve non-invasive observation and measure alterations in ICP, they are not applicable to continuous monitoring of the pressure levels and the exact values cannot be obtained, which further limits their clinical application.

In the present study, we used flexible electronics, which can provide continuous non-invasive extracorporeal pressure measurements at multiple sites. The pig-skin soft tissue expander device we used was able to simulate the real condition of patients with osteofascial compartment syndrome. According to our analysis, the external pressure was positively correlated to the internal pressure, which indicates that the external pressure can reflect changes in the internal pressure to some extent.

In our study, it was also found that the measurable minimal internal pressure would decrease along with the increase of the pig skin's thickness. By extending the fitting curve, we found that the pressure level at the thickness of 0 mm (red dot in **Figure 3**) was approximately equal to the lowest internal pressure, directly measured by the soft tissue expander sensor. This finding further confirmed our speculation: the increasing phases were induced by the soft-tissue expander device and the two plateauing phases resulted from the pig skin model. After adding the acrylic panel, the measured range increased, with the lowest measurable internal pressure being 5 mmHg. Moreover, the alteration in the external pressure was also greater than those in other groups.

It was also observed that, without the presence of the soft tissue expander device, the measurable minimal internal pressure would decrease with increasing pig skin thickness. This observation is in line with physiologic conditions, in which youth with thicker skin are more likely to develop compartment syndrome than the elderly with thinner skin. Furthermore, the internal and external plateauing pressure levels measured by the sensor also increased with the thickness of the pig skin, which was also in accordance with the actual condition.

Our results show that the minimum internal pressure measured by the sensor increased with the initial internal pressure, which was as expected. However, the internal and external plateauing pressure levels decreased with the increase of the initial internal pressure. This was speculated to be due to the limited measurable changes in the external pressure, at the presence of rather high initial internal pressure. This could be a limitation of our sensor in clinical practice. For instance, if a patient with a fracture had relatively high ICP at admission (initial internal pressure), the measurable range of external pressure detectable by the sensor would be rather limited. Therefore, more flexible pressure sensors with higher sensitivity need to be developed in the future to address this issue.

Based on the results above, ICP could be detected by indirectly measuring the external pressure with a flexible pressure sensor. This non-invasive method may be a solution to the shortage of traditional measurement methods and contribute to the early diagnosis of ACS.

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Disclosure of conflict of interest

None.

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