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Original Article

Corrugated Sheet of Unsintered Hydroxyapatite Poly-L-Lactide for Sternal Fixation: A Preclinical Study

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Purpose: To stabilize the sternum after median sternotomy, unsintered hydroxyapatite poly-L-lactide (u-HA/PLLA) sternal pins are frequently used in Japan. However, sternal pins are ineffective in the fragile bone marrow. Thus, a corrugated sheet made of u-HA/PLLA was developed as a new sternal fixation device.

Methods: To examine the effects of the device, we measured the shear force using a sternal model and cadaver. The shear force of the corrugated sheet, sternal pin, and simple wire was compared. The device size was determined after reviewing the sternal computed tomography (CT) of 128 patients.

Results: The shear force of the model with the corrugated sheet (286 [256–295] N) was higher than that with sternal pins (135 [134–139] N, $p = 0.03$) and simple wire (94 [90–104] N, $p = 0.03$) at 2-mm displacement. In the cadaver test, the shear force of the sternal halves with the device was about two times higher than that without the device. Retrospective CT showed that 18-mm wide device applies to 99% male and 87% female patients at the fourth intercostal level.

Conclusion: The corrugated sheet might provide a stronger fixation effect in the fragile bone marrow. The device width was modified to 18 mm to be applicable for most Japanese patients.

Keywords: corrugated sheet, fragile bone marrow, Super Fixsorb WAVE, u-HA/PLLA

Introduction

Even though the mini-thoracotomy approach is gaining popularity, the median sternotomy remains the mainstream approach in cardiovascular surgery. Simple wire cerclage is usually used for sternotomy closure. However, sometimes it has an insufficient fixation effect on the sternal halves,[1)] resulting in sternal displacement.

The bioresorbable unsintered hydroxyapatite poly-L-lactide acid (u-HA/PLLA) sternal pin (Super Fixsorb 30, Teijin Medical Technologies Co., Ltd., Osaka, Japan) is designed for implantation in the sternal bone marrow and is widely used in combination with the sternal wire for sternal fixation in Japan.[1,2)] The sternal pin is expected to prevent anteroposterior and craniocaudal movement for improved stability and to promote sternal fusion.

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However, when the sternal pin is implanted into the fragile bone marrow, the fixation effect is insufficient because the pin cannot stay firmly in the weak reticulum network of the bone marrow.

To solve this problem, we developed a corrugated sheet made of u-HA/PLLA. This new sternal fixation device is expected to be more effective than a sternal pin for sternal stability, especially in the fragile bone marrow.

The purpose of this study was to investigate the effect of the corrugated sheet in a biomechanical test using sternal models and human cadaver and to modify the size of the corrugated sheet based on the computed tomography (CT) data of the sternal bone marrow size.

Materials and Methods

The research ethics committee of Tokyo Medical and Dental University approved this study (M2000-1806). The research ethics committee of Ramathibodi Hospital, Mahidol University, Thailand approved the cadaver test (No MURA2016/133). The cadaver test was performed under a contract research agreement between the Tokyo Medical and Dental University, and the Faculty of Medicine Ramathibodi Hospital, Mahidol University (A16-173).

New sternal fixation device

The corrugated sheet is created by adding heat treatment to a flat sheet of u-HA/PLLA[2)] (Super Fixsorb MX40, Teijin Medical Technologies Co., Ltd.). The sheet is made up of 40% HA, and 60% PLLA by weight (**Fig. 1A**) and is expected to increase the retention force against shear stress. To ensure easy insertion, both sides of the corrugated sheet were shaped to have spines at all inflection points. The effectiveness of this new sternal fixation device was compared to a commercially available sternal pin, which is made of 30% HA and 70% PLLA. Both the devices are bioresorbable.[3)]

Biomechanical test

Artificial sternal model

The biomechanical test using the artificial sternal model was performed at the Medical Research Laboratory of Teijin Medical Technologies Co., Ltd. The sternal model consisted of two components: the cortical bone portion (50 mm × 80 mm × 14 mm) was made of monomer casting nylon (Standard, Misumi Group Inc., Tokyo, Japan), and the bone marrow portion (32 mm × 11.5 mm × 6 mm) was made of 80 kg/m^3 density polyurethane foam (Block 5pcf, #1522-23; Pacific Research Laboratories, Vashon, WA, USA).

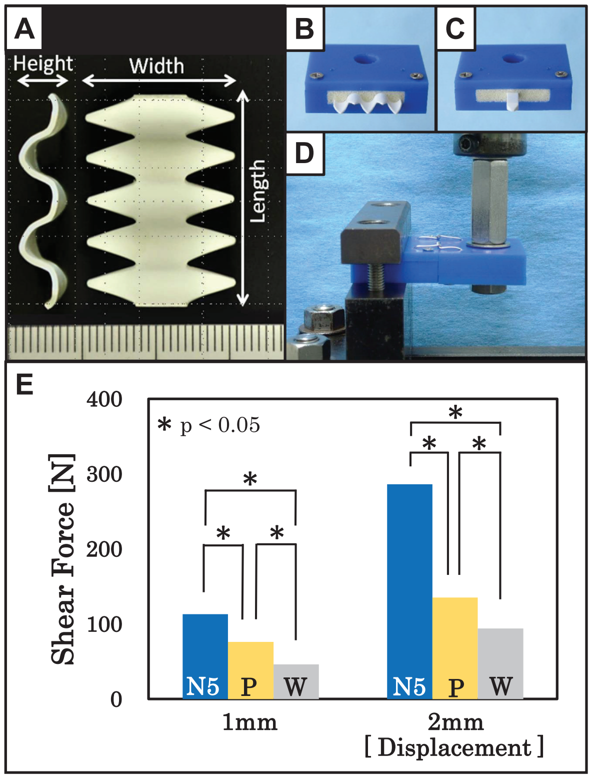

Fig. 1 (**A**) A new corrugated sheet sternal fixation device. (**B**) The new sternal fixation device with five inflection points is inserted into the sternal model. (**C**) Sternal pin inserted into the model. (**D**) Setting of the shear force test in the sternal model. (**E**) Shear force values at 1 mm and 2 mm of displacement according to the type of fixation. N5: New sternal fixation device with five inflection points; P: sternal pin; W: simple wire cerclage. *p <0.05.

Shear force of the sternal model with different devices

In the new device group (n = 5), the corrugated sheet device with five inflection points (21 mm × 30 mm × 5 mm) was inserted into the pseudo-sternal half. The two portions of pseudo-sternal half were approximated with two stainless steel wires (No. 6; Ethicon, Inc., Somerville, NJ, USA) by a torque limiter up to 27 N · cm (**Fig. 1B**). In the pin group (n = 5), a sternal pin (5 mm × 3 mm × 23 mm) was inserted into the pseudo-sternum and fixed in the same fashion (**Fig. 1C**). In the wire group (n = 5), the pseudo-sternum was cerclaged with stainless steel wires, and no device was inserted.

One pseudo-sternal half was fixed to the testing machine (Autograph AG-20kNXD, Shimadzu Co., Kyoto, Japan), and the other half was pushed down by a rod attached to a load cell. (**Fig. 1D**). Shear force was measured at the points of 1 mm and 2 mm displacement of the pseudo-sternal half.

Shear force of the sternal model with the corrugated sheet with different inflection points

The shear force of the sternal model using the corrugated sheet with 3 or 4 inflection points was also measured. Then, the shear force that induced 2-mm displacement was compared among the 3, 4, and 5 inflection points (n = 5 per group).

Cadaver test

Measurement of sternal bone marrow hardness

A bone hardness meter (Teijin Medical Technologies Co., Ltd.) was specially designed to measure the stiffness of sternal bone marrow (**Fig. 2A**). The hardness scale, which ranged from 0 to 7, was displayed on the sidewall of the tool. Zero indicated “most fragile,” and 7 indicated “hardest.” The scale was converted to MPa (Megapascal) using a conversion chart for this tool (**Fig. 2C**). Median sternotomy using an oscillating saw was performed in 17 human cadavers. The tip of this hardness meter was pushed against a cross-section of the sternal bone marrow, and the hardness scale was measured. The feasibility of device insertion, according to the hardness of the bone marrow was evaluated.

Selection of device size

The width of the corrugated sheet was designed as 21 mm, and the height was designed to have three variations (3 mm, 4 mm, and 5 mm). The height of the corrugated sheet was selected according to the height of the sternal bone marrow of each cadaver.

Insertion procedure of the new sternal fixation device

After placing six stainless steel wires (No. 6 Ethicon, Inc., Somerville, NJ, USA) through both sternal halves, two corrugated sheets with five inflection points were inserted into the bone marrow of the sternal body, using an insertion assisting instrument specially made for the device (**Fig. 2D**). Then, both the sternal halves were approximated by cross traction of the wires, and all the wires were cerclaged by twisting with a large needle-driver followed by a torque limiter up to 27 N · cm.

Shear force test in the anteroposterior direction

In nine cadavers with successful implantation of the corrugated sheet, the sternum was extracted en bloc by cutting the ribs and sternoclavicular joint using an oscillating saw. The sternum mass was cut into 7-cm wide and 6-cm long segments, to include one corrugated sheet with five inflection points and two stainless steel wires at the second and third intercostal levels (**Fig. 2E**). One side of the sternal halves was fixed to a vice with a spiked surface. A force gauge (NIDEC-SHIMPO Corporation, Kyoto, Japan, FGP-50) was attached to a simplified mold load cell stand (NIDEC-SHIMPO Corporation, FGS-50H), and a stainless rod with a diameter of 1.5 cm was fixed to the tip of the force gauge. The load was applied to the opposite side of the sternal halves with the rod (**Fig. 2F**). The maximum shear force at 2-mm and 5-mm displacement was measured using a digital indicator (ID-C1012C, Mitutoyo Corporation, Kanagawa, Japan).

Shear force test with and without the corrugated sheet in the same specimen

In three cadavers, shear force at 2-mm and 5-mm displacement were measured both with and without the corrugated sheet in the same specimen. Before the insertion of the corrugated sheet, the shear force of the sternal halves with simple wire cerclage was measured. Then, the wires were released, and the corrugated sheet was inserted into the bone marrow of the same specimen. Again, the wires were tightened, and the sheer force with the corrugated sheet was measured.

Evaluation by CT

In six cadavers, the implanted device position was evaluated by CT scan conducted at 1-mm width intervals, before the shear force test.

Retrospective CT study

We reviewed the preoperative CT of 128 patients (83 men and 45 women) who underwent cardiovascular surgery at our institution during 2012. The age was 69 [60–75] years in men and 71 [67–77] years in women. Body surface area was 1.70 [1.61–1.79] m^2 and 1.43 [1.36–1.54] m^2, respectively. We measured the width and height of the sternal bone marrow at six axial slices to modify the size of the corrugated sheet to fit Japanese patients. Those six axial slices were obtained at the level of the second intercostal space (i.c.s 2), third rib (rib 3), third intercostal space (i.c.s 3), fourth rib (rib 4), fourth intercostal space (i.c.s 4), and fifth rib (rib 5).

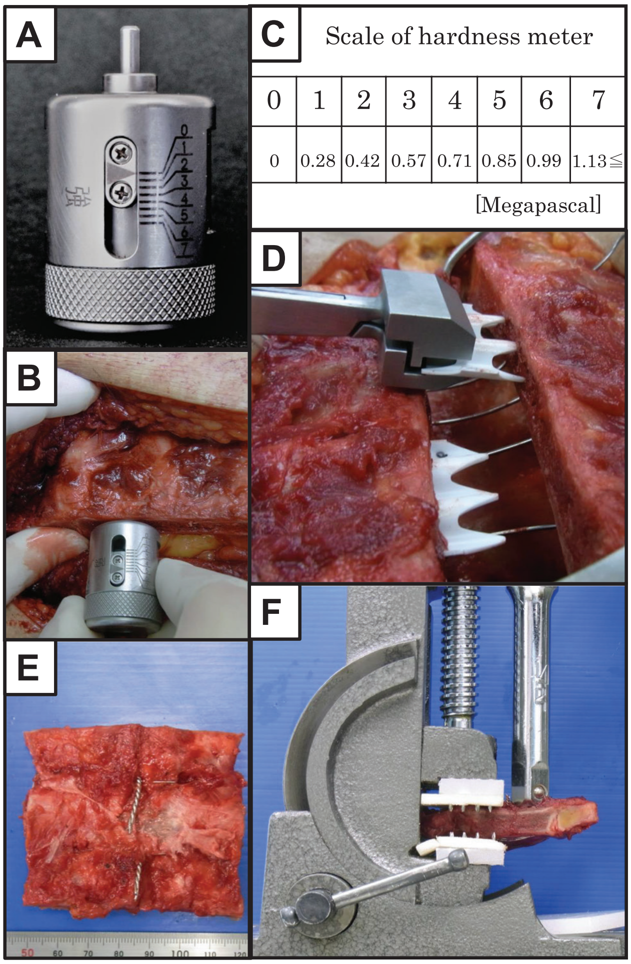

Fig. 2 (**A**) The hardness meter; the meter appears on the sidewall of the tool. (**B**) The tip of the hardness meter was pushed against the cross-section of the sternal bone marrow. (**C**) Conversion chart of hardness meter. (**D**) Two pieces of the new sternal fixation device were inserted into the sternal bone marrow using insertion assisting instrument specially designed for the device. (**E**) The specimen of sternal halves cut into 7-cm wide and 6-cm long segments. (**F**) Shear force test. One side of the sternal half was fixed to the vice with a spiked surface. The load was applied to the other side of the sternal half with the stainless rod.

Statistical analysis

Values are presented as median [interquartile range]. The Kruskal–Wallis test was used to compare the shear force among the three groups in the biomechanical test. Post hoc testing was performed using the Steel–Dwass method. The Mann–Whitney U-test was used to compare the shear force between the two groups in both biomechanical and cadaver tests. All statistical analyses were performed with EZR (Saitama Medical Center, Jichi Medical University, Saitama, Japan), which is a graphical user interface for R (The R Foundation for Statistical Computing, Vienna, Austria).[4] Statistical significance was set at a p value <0.05.

Results

Biomechanical test

The shear force of the sternal model with different devices

There were significant differences between the shear force values of any two groups among the three groups at both 1- and 2-mm displacement (**Fig. 1E**). At 2 mm of displacement, the shear force of the model with the corrugated sheet with five inflection points (286 [256–295] N) was higher than that with sternal pins (135 [134–139] N, p = 0.03) and simple wire (94 [90–104] N, p = 0.03).

Shear force of the sternal model with the corrugated sheet of different inflection points and sternal pin

At 2 mm of displacement, the values of shear force were 198 [190–204] N, 233 [216–246] N, and 286 [256–295] N for the corrugated sheet with 3, 4, and 5 inflection points, respectively. There was a significant difference in the shear force value between the 3 and 5 inflection points at 2-mm displacement (p = 0.03).

Even with the corrugated sheet with three inflection points, the shear force value was higher than that of the pin group (135 [134–139] N) at 2-mm displacement (p = 0.008).

Cadaver test

Correlation between age and the hardness of the sternal bone marrow

In nine out of 17 cadavers, the corrugated sheets were successfully implanted. **Figure 3A** shows the relationship between the hardness of the sternal bone marrow at the third rib level and the age of the cadaver. The median age of the cadaver to which the corrugated sheet was implantable and unimplantable was 62.0 [58.5–74.0] years and 44.5 [30.8–51.3] years, respectively (p = 0.006). The hardness of sternal bone marrow to which the corrugated sheet could be implanted was hardness scale 5 (0.85 MPa) or less. The corrugated sheet was successfully implanted in almost all cadavers above 55 years of age.

In three of the nine cadavers, the tip of both edges of the corrugated sheet had to be cut by 1 to 2 mm because of the limited width of the sternal bone marrow.

The shear force values of the sternum with the corrugated sheet

In nine cadavers with the implanted corrugated sheet, the shear force of the sternal halves with the device at 2-mm and 5-mm displacement were 67.1 [57.8–76.9] N and 147 [112–153] N, respectively.

The difference of shear force with and without the corrugated sheet

In three of the nine cadavers with the implanted corrugated sheet, the shear force tests both with and without the device were conducted. The shear force of the sternal halves with the corrugated sheet was about two times higher than that without the device at both 2-mm and 5-mm displacement (**Fig. 3B**).

Evaluation by CT scan in cadaver test

CT scan showed that all the corrugated sheets were positioned properly, supporting the sternal halves firmly from the inside (**Fig. 3C**).

Retrospective CT scan study

The width of the bone marrow of sternal body at each slice is shown in **Fig. 4A**. The width of the rib 3 level was the narrowest, and that of the i.c.s 4 level was the widest. This CT data indicated that 21-mm wide corrugated sheet which was designed in the preclinical cadaver study was applicable to 55% of male patients and 24% of female patients at the rib 3 level, and was applicable to 99% of male patients and 71% of female patients at the i.c.s 4 level. On the other hand, if the width of corrugated sheet was modified to 18 mm, it could apply to 87% of male patients and 56% of female patients at the rib 3 level and 99% of male patients and 87% of female patients at the i.c.s 4 level. The height of the sternal body bone marrow was 3 mm or more in almost all patients (**Fig. 4B**).

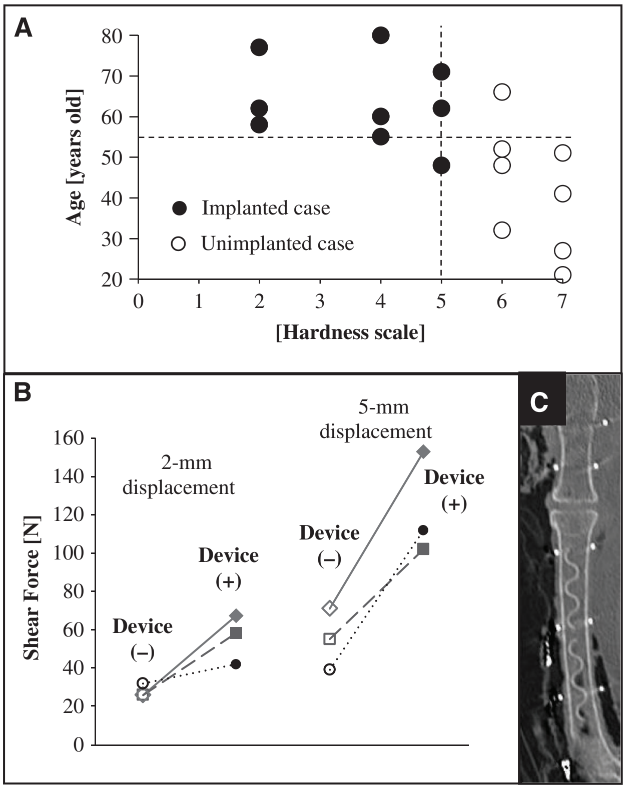

Fig. 3 (**A**) Scatter plot demonstrating the correlation between age and hardness of the sternal bone marrow. Black circles indicate cadavers with the implanted new sternal fixation device. White circles indicate cadavers to which the new device could not be implanted. (**B**) The difference in shear force with or without the new sternal fixation device at 2-mm and 5-mm displacement. (**C**) Computed tomography sagittal scan after device insertion.

Discussion

Although simple wire cerclage is expected to provide sufficient fixation effect, it sometimes cannot prevent the displacement of sternal halves. The sternal pin is a fixation device implanted in the sternal bone marrow to prevent displacement. However, it provides insufficient fixation for fragile bone marrow. To solve this problem, we developed a corrugated sheet type sternal fixation device to be used in combination with the sternal wire. Sternal halves were firmly supported by the internal corrugated sheet fixation and the external wire cerclage fixation.

We compared the effect of the corrugated sheet, simple wire cerclage, and sternal pin in the present study. In biomechanical tests, even with three inflection points, the corrugated sheet was more effective than both the simple wire cerclage and the sternal pin. In the cadaver test, the shear force of the sternal halves with the corrugated sheet with five inflection points was about two times stronger than that without the device in the same specimen. Thus, the corrugated sheet stabilizes the separated sternum more firmly than the simple wire cerclage.

The most characteristic feature of the new sternal fixation device is its corrugated shape. The corrugated shape increases the retentive force against shear stress as compared to a flat sheet. Moreover, the structure of the corrugated sheet in combination with the anterior and posterior cortical bony sternal plate is similar to the truss structure in corrugated cardboard. In general, the truss structure is resistant to deformation and is applied to the

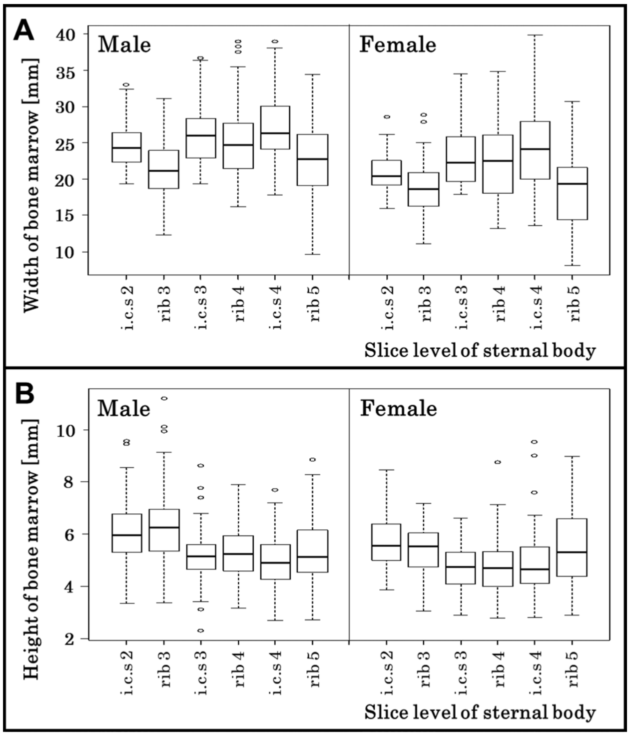

Fig. 4 (**A**) Width of sternal body bone marrow in male and female patients. (**B**) Height of sternal body bone marrow in male and female patients.

architecture of the bridge pier and tower, bicycle frame, and corrugated cardboard.

The corrugated sheet was made of the same material as the u-HA/PLLA sternal pin, because of its high strength, osteoconductivity, and bioresorbability.[5)] This material has higher strength than human cortical bone and can maintain its strength for at least 6 months after implantation, during which sternal bone healing is mostly achieved.[5,6)] Moreover, owing to osteoconductivity of our new device, sternal bone healing is expected to be faster. The corrugated sheet will be completely reabsorbed 4–5 years after implantation.[7)] This bioresorbable feature is advantageous for preventing late infection of the corrugated sheet.

As reported previously, no correlation was observed between the sternal width and body surface area in either male or female bodies.[8)] In other words, we cannot predict the width of the bone marrow of the sternum based on the size of the patient. Therefore, it is recommended to check the width of the bone marrow of the sternum using preoperative CT scan. When the bone marrow space is limited for implantation, the corrugated sheet can be cut to have fewer inflection points and then implanted. Else, the tips of the corrugated sheet must be cut to reduce the width of the corrugated sheet. Actually, in three cadavers, the corrugated sheet could not be implanted because of the limited width of the sternal bone marrow. In those cases, we had to cut the tips of the device to make the width narrower. Additionally, according to the retrospective CT results, 21-mm device can be implanted in only 55% of male patients and 24% of female patients at the third rib level. Eventually, the width of the device was modified to 18 mm with height variations of 3 mm, 4 mm, and 5 mm to make implantation possible in most Japanese patients.

Rigid plate fixation using a metal plate and screw is an alternative way of sternotomy closure. Some studies reported that sternotomy closure with metal plate and screw resulted in improved sternal healing compared to simple wire cerclage.[6,9,10)] For patients with hard sternum, fixation with metal plate and screw can prevent anteroposterior displacement of the sternal halves sufficiently. However, for patients with fragile cortical bone, the plate may not be fixed firmly to the sternum using a screw, due to insufficient anchorage. Additionally, the metal plate continues to be a foreign material for the rest of the patient's life because the metal plate does not have bioresorbability, and can be a potential source of infection at any time following surgery.

Our new sternal fixation device became commercially available as Super Fixsorb WAVE (Teijin Medical Technologies Co., Ltd.) and will also become commercially available as OSTEOTRNS-MX WAVE outside Japan.

A randomized controlled trial evaluating the effect of this new sternal fixation device is now ongoing. Gaining stability after sternotomy reduces postoperative sternal pain and promotes bone healing. Moreover, postoperative physical therapy of the upper body can be started earlier, leading to early rehabilitation after open-heart surgery.

Study limitations

The limitation of this study is that the sternal models used in the biomechanical test do not reflect the diversity of the patients in the clinical setting. We were also limited by the number of bodies available for the cadaver test. Therefore, statistically analysis of the device effectiveness in the cadaver test was precluded.

Conclusions

The biomechanical and cadaver tests suggest that the corrugated sheet type u-HA/PLLA sternal fixation device improves sternal stability after sternotomy. This device provides stronger sternal fixation than the simple wire cerclage and sternal pins, especially in patients with fragile bone marrow. The width of the device was modified to 18 mm from 21 mm to enable its use in most Japanese patients.

Acknowledgment

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Disclosure Statement

Drs. Kuroki and Arai received a research grant from Teijin Medical Technologies Co., Ltd. (2A252, 2016), and also hold a patent on this new sternal fixation device (P6502161, 2019). Some parts of our study method were recommended by this company; however, the authors had full control of the results, data analysis, and production of the written report.

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