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ORIGINAL ARTICLE • KNEE - OSTEOTOMY

Advantages of creation of holes and removal of air in artificial bone for early bone formation when used artificial bone as a gap filler in open wedge high tibial osteotomy

Yasuaki Tohma[1,2] · Ryohei Takeuchi[3] · Yasuhito Tanaka[2]

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Abstract
Recently, many facilities perform open wedge high tibial osteotomy (OWHTO) using artificial bone as a gap filler. However, there are many cases in which artificial bone is used without a clear purpose. We recommend a surgical technique to promote early synostosis between artificial bone and recipient bone due to mechanical support especially in the early stage after OWHTO. At our hospital, beta-tricalcium phosphate (β-TCP) with 60% porosity is used in OWHTO. Initially, a wedge-shaped block-type β-TCP, as large as possible, was inserted into the gap. However, from the standpoint of initial mechanical support, we changed the artificial bone size and created intentional holes. Furthermore, we removed air bubbles from β-TCP. We evaluated the synostosis on the basis of clinical results and diagnostic imaging. As a result of creating holes and removing air from the artificial bone, a trend toward faster synostosis was noted, especially at the early stage. No adverse events such as tibial plateau fracture, lateral cortical fracture, plate and screw failure and correction loss due to reducing the size of the artificial bone occurred, but placement of the artificial bone in contact with cortical bone and surface contact installation with the recipient bone tissue was important. When using artificial bone in OWHTO, holes formation and removal of air from the artificial bone are recommended for faster synostosis between artificial bone and recipient bone in the early stage after surgery. Artificial bone should be used, with attention to its positioning and shape, for efficient mechanical support.

Keywords Open wedge osteotomy · Artificial bone · Beta-tricalcium phosphate · Bone formation · Hole formation · Air removal

Introduction

In aging societies, knee osteoarthritis cases have been increased, and joint replacement surgeries are currently being performed worldwide. However, reconsideration of conservative joint-preservation surgery using high tibial osteotomy (HTO) is gaining popularity in various countries, taking into consideration patients' preoperative high performance. Recently, open wedge HTO (OWHTO), which allows earlier weight bearing, has been widely implemented owing to the development of the locking plate. Regarding usage of artificial bone as a gap filler for OWHTO, stable results from OWHTO without using artificial bone have been reported [1, 2]. On the other hand, it was reported that the use of artificial bone in OWHTO enables early safe weight bearing [3–6]. Postoperative complications resulting from early full weight bearing include tibial plateau fracture, lateral cortical fracture, plate and screw failure, correction loss, non-union, delayed union, and possible local infection [5]. The use of beta-tricalcium phosphate (β-TCP) and a locking plate system improves the initial axial and, possibly, the rotational stability at the osteotomy site in comparison with those on using methods that leave the osteotomy gap open [7]. Artificial bone is expected to distribute the stress applied to the osteotomy site across the artificial bone wedge and the TomoFix™ plate (Johnson & Johnson, New Brunswick, New Jersey, USA) [6]. Moreover, concerning loss of

✉ Yasuaki Tohma
yatohma@naramed-u.ac.jp

1 Department of Orthopaedic Surgery, Nara City Hospital, 1-50-1, Higashi-Kidera-cho, Nara, Nara, Japan

2 Department of Orthopaedic Surgery, Nara Medical University, Kashihara, Nara, Japan

3 Department of Joint Surgery Center, Yokosuka City Hospital, Yokosuka, Kanagawa, Japan

correction, its use was recommended in the case of a large varus deformity or large gap in the OWHTO [5, 8, 9].

Previous literature reports state that artificial bone for OWHTO must have high clinical utility, high osteoconductivity, and high absorbability [4]. From this standpoint, recently, βTCP has been used as a gap filler during OWHTO. We have conducted basic research on osteogenesis using artificial bone and have reported our results [10, 11]. The aim of the current study is to report a basic and clinically effective surgical technique for artificial bone as a gap filler in OWHTO to allow safe, early load bearing.

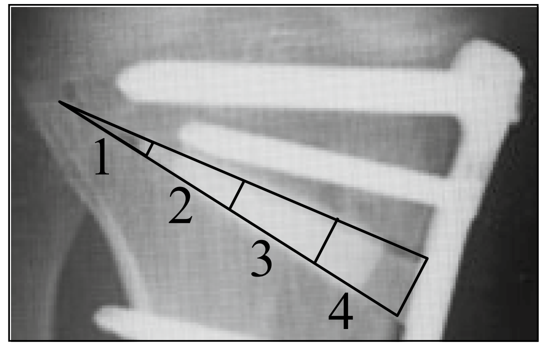

Fig. 1 Zone classification. The gap opened in OWHTO is divided into equal quadrants

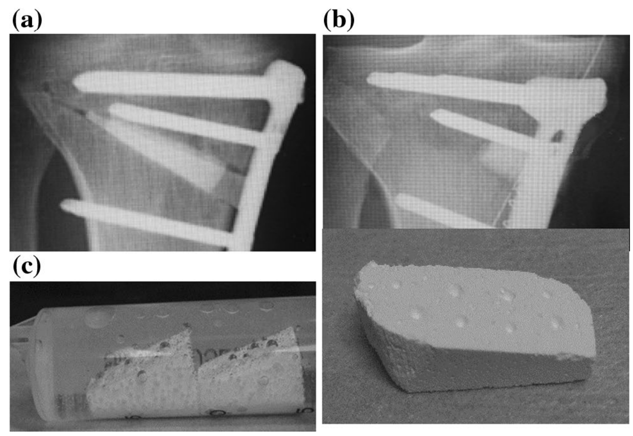

Fig. 2 Comparative groups. **a** Artificial bone in Group 1. Artificial bone placed extending to zone 2 of the opening. **b** External appearance of artificial bone of Group 2. Artificial bone was placed with a width of 30% of the opening, and several holes were formed using a 1-mm-diameter drill bit in the wedge-shaped artificial bone in the longitudinal direction. **c** Artificial bone in Group 3. Washing and removal of air technique in Group 3. Artificial bone in a syringe filled with a solution. Washing and removal of air in artificial bone was performed by performing manual suctioning. Many bubbles were removed from inside the artificial bone

Methods

Operative procedure

Patients

This study included patients with a diagnosis of osteoarthritis of the knee or osteonecrosis of the medial femoral condyle who underwent OWHTO between 2012 and 2017. Ninety patients who underwent OWHTO surgery performed by the same surgeon (author) using the same artificial bone during this period were initially enrolled. However, 36 patients were lost to follow-up. We surveyed 54 patients who were available for postoperative follow-up investigation.

Surgical procedure

OWHTO was performed in accordance with the usual surgical procedure [1–3]. Medial fixation used the TomoFix™ plate; the artificial bone used was a β-TCP (OSferion®, Olympus Terumo Biomaterials, Tokyo, Japan) with 60% porosity, developed taking into consideration autologous bone replacement and use in load-bearing areas. Standing and walking exercises began from the day after surgery. The gap opened in OWHTO was divided into equal quadrants [12] (Fig. 1). When OWHTO was first performed, artificial bone was inserted into zone 2 (Group 1; Fig. 2a) to distribute loading over a broader area.

Creation of holes and removal of air

Based on our experience in basic research on bone formation concerning the inner region of artificial bone [10], we started creating holes 1 mm in diameter with the aim of increasing inflow of bone marrow fluid into the artificial bone from the recipient bone tissue. Several holes were formed using a 1-mm-diameter drill bit in the wedge-shaped artificial bone in the longitudinal direction. Moreover, the size of the artificial bone was changed to the level of the medial 30% of the opening (Group 2; Fig. 2b). After that, from the standpoint of quickening bone formation, washing and removal of air in the artificial bone were added, aiming to improve the invasion of bone marrow (Group 3). The procedure for removal of air involves the use a syringe into which the shaped artificial bone is inserted. After inserting the artificial bone, normal saline is aspirated into the syringe. When the normal saline is pulled into the syringe, negative pressure occurs. As a result, the air within the artificial bone is removed (Fig. 2c).

Evaluations

The clinical results were obtained by evaluating the Japanese Orthopaedic Association score (JOA score; 0–100) before the operation and 1 year postoperatively. The synostosis from new bone growth at the interface between the artificial bone and the recipient bone tissue was evaluated by measuring the time to reach various stages defined as follows, by consulting past references [4, 8].

The evaluation of the synostosis was performed based on radiological assessment. We used an anteroposterior view radiograph and divided the synostosis process into three stages so that we could grade the synostosis simply. Stage 1 is when new bones are formed around the artificial bone and both interfaces between the artificial bone and the recipient bone tissue are partially indistinct (Fig. 3a), stage 2 is when one surface is indistinct (Fig. 3b), and stage 3 is when both interfaces have become indistinct (Fig. 3c). Moreover, we measured the tibial posterior slope (TPS) for evaluating the role of mechanical support in the three groups. The TPS was measured using the previous method as Ref. [13, 14]. We used a lateral view radiograph and measured the angle formed by the line drawn perpendicularly to the diaphyseal axis and the line drawn using the highest two points of the anterior and posterior edges of the plateau. The change of the TPS was calculated by subtracting the preoperative angle from the postoperative angle. Also, we considered whether there were cases thought to have other complications related to the use of artificial bone, such as crush of β-TCP.

We used the Kruskal–Wallis *H*-test for statistical significance, and the Mann–Whitney *U*-test with Bonferroni correction as a post hoc test for comparing the synostosis of the groups. The Mann–Whitney *U*-test was used to compare the change of the tilt of the TPS.

Results

There were no significant differences in the preoperative and postoperative femorotibial angle (FTA). Moreover, there was no significant difference in the clinical results between the groups (Table 1a). Concerning the synostosis in each group, there were significant differences in stage 1. Creation of holes and removal of air in the artificial bone (Group 3) resulted in earlier synostosis at the interface between artificial bone and the recipient bone tissue at an early stage (Table 1b). Comparing stages 2 and 3, there were no significant differences. However, the procedure of creating holes and removal of air showed a trend toward earlier synostosis. There were no differences regarding the size of the artificial bone and the TPS. In retrospective evaluations of the imaging, there were several cases in which the artificial bone was not placed at the posterior cortical bone (Fig. 4a; Left), which has mechanical strength, resulting in the support being provided by cancellous bone. These cases had a tendency toward increased TPS. In addition, the insertion of a large artificial bone size was found to result in a point-contact placement, in which only a portion of the artificial bone was in contact with the recipient bone tissue.

Discussion

Artificial bone size

Initially, a large section of artificial bone was inserted to create broad contact with the recipient bone tissue, but doing so caused cases of point contact in which there was only contact between the two bones at certain areas (Fig. 4b; left). In this case, the entire artificial bone could not effectively load-bear. Absorption of 60% porosity β-TCP into bone tissue has been reported to take 7 years [15], and absorption into the body is considered dependent on porosity, volume, shape, and placement position [4]. Early bone formation filling the narrower gaps at zones 1 and 2 has been observed, and the clinical result did not change significantly despite changing the size of the artificial bone in this study. Taking into consideration the absorption of artificial bone and initial mechanical support for loading stress, making a point to insert a larger piece is considered unnecessary as long as artificial bone is indeed being placed. β-TCP was only minimally resorbed in a non-loading rat calvarial model [16]. Moreover, the resorption

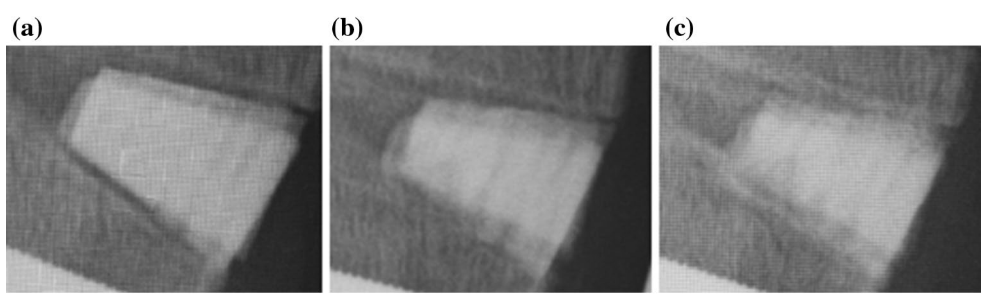

Fig. 3 Classification of bone formation at the interface between artificial bone and recipient bone tissue. **a** Stage 1: new bones are formed around the artificial bone. The interfaces between the artificial bone and the recipient bone tissue are partially indistinct. **b** Stage 2: one surface is indistinct. **c** Stage 3: both interfaces have become indistinct

Table 1 Comparison between each groups. **(a)** Number, preoperative and postoperative femorotibial angle (FTA), opening distance, and preoperative and postoperative JOA score of each group. **(b)** Degree of synostosis at the interface between the artificial bone and the recipient bone tissue evaluated radiographically of each group. **(c)** Change in the degree of tilt of the TPS after OWHTO

(a)

	Group 1	Group 2	Group 3
Number	12	13	29
Preoperative FTA	181.8 ± 3.0	181.0 ± 1.6	179.8 ± 2.2
Postoperative FTA	169.3 ± 3.6	168.4 ± 2.2	168.2 ± 2.0
Opening distance (mm)	12.5 ± 2.3	13.8 ± 1.7	11.5 ± 2.1
Preoperative score	65.0 ± 13.0	72.5 ± 14.1	72.5 ± 14.4
Postoperative score	92.4 ± 5.0	93.0 ± 5.5	92.2 ± 7.0

(b)

Stage	Group 1	Group 2	Group 3
1	1.9±0.3	1.8±0.4	1.4±0.7
2	3.8±1.5	3.1±0.8	3.0±1.6
3	6.2±3.1	5.3±1.6	5.4±1.8

**$p<0.05$ *$p<0.01$

(c)

	Poor contact group	Good contact group
Change of slope (degree)	2.8 ± 2.4	0.3 ± 1.5

*$p<0.01$

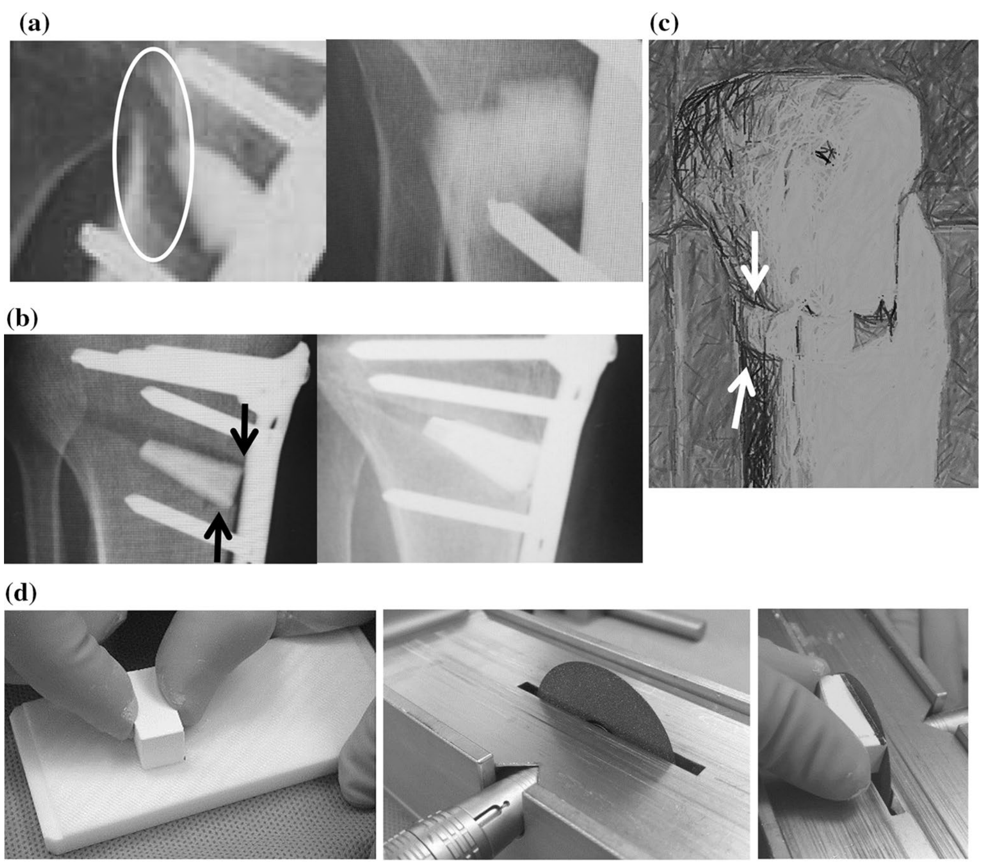

Fig. 4 Surgical procedure. **a** X-ray image. Left, the artificial bone was not placed between the stronger sections of posterior cortical bone (circle; poor contact). Right, the artificial bone with good placement (good contact). **b** X-ray image. Left, the artificial bone is only contacting a portion of the recipient bone tissue (arrow). Right, the artificial bone is shaped and placed to obtain a broad area of contact. **c** Bone model. The artificial bone is placed in contact with the medial and posterior cortical bone. **d** Procedure of forming the wedge-shaped artificial bone. Left, ceramic file. Center, the blade of electric saw for the artificial bone. Right, the side of this blade is like a file

of β-TCP occurs in load-bearing environments of long bones [17, 18]. Considering the efficacy of surface broad contact to provide mechanical support (Fig. 4b; right), we used a special saw and ceramic file (Olympus Terumo Biomaterials, Tokyo, Japan) to accommodate the gap. The side of this saw's blade is like a file. The side of this blade is used as an electric file, and we can easily form the fitted wedge-shaped bone filler (Fig. 4c). Therefore, from the standpoint of mechanical strength and resorption, the placement position of artificial bone is more important than its size.

Creation of holes

Structure has been reported to be important taking into consideration mechanical strength and bone formation, when developing artificial bone [10, 11, 18]. Pore size differences can change cell infiltration into the artificial bone and bone formation. Although bone ingrowth has been confirmed into ceramic disks both with pore diameters of 200 and 500 µm, the 500 µm disk showed superior bone formation inside [10]. Also, based on reports on pore size and bone ingrowth [11, 19] and reports on vascular tissue regrowth depending on pore size [20], the effect of the surrounding environment is important for bone formation at the artificial bone interface. Thus, holes with a 1 mm diameter were formed in the artificial bone during surgery with the expectation of abundant bone marrow fluid flow into the interior of the artificial bone from the recipient cancellous bone. The holes were formed in the longitudinal direction due to mechanical considerations. We considered it sufficient to form a number of holes that takes into consideration the strength of the artificial bone. This simple surgical procedure allows bone marrow-derived cells to quickly infiltrate into the artificial bone.

Removal of air in artificial bone

There are a variety of theories in regenerative medicine regarding the introduction of cells into porous bodies. Studies of bone formation in composites of porous ceramics and cells have previously been performed, but only immersed in cell-containing solutions [10]. Air remaining in the artificial bone is considered undesirable. Concerning the research of cell seeding into a porous scaffold, it was reported that the penetration of cell suspension is partly interrupted by the normobaric air remaining in the pores [21]. The removal of air bubbles in the pores in the ceramic allows for easy invasion of cells into pore areas [11]. To efficiently infiltrate liquid into porous materials, it is important to remove the air inside the pore [22]. In OWHTO, the artificial bone is in contact with the recipient cancellous bone. As abundant mesenchymal cells are included in the bone marrow, active new bone formation in the artificial bone was expected due to the infiltration of bone marrow. Therefore, we started removing air from the artificial bone with the aim of improving the smooth infiltration of bone marrow. Concerning the method of air removal, the use of a low-pressure system when introducing cells into a porous body [21–23] has been reported to show more favorable cell infiltration when residual air in the porous body is removed [11]. Methods of introduction include a low-pressure system, a pipette technique [24], and the use of a syringe [25]. In this study, considering synostosis, the effect caused by the creation of holes and removal of air was indicated, especially at the early stage after OWHTO. Therefore, rapid synostosis from new bone formation could be expected by performing both the creation of 1 mm holes and removal of air. Due to convenience during surgery, we performed removal of air in artificial bone using a syringe to aspirate normal saline solution. At that time, various cells may be included [23, 26], and it is recommended that this be performed at a low pressure, taking into consideration the cell loading efficiency [21–23]. In addition, from reports on the effect of sustained drug release and the inclusion of antibiotics [27, 28], the inclusion of antibiotics is considered effective to combat infections and is used at our hospital as well. As a result, this simple surgical procedure improves early bone formation at the interface of artificial bone and recipient bone, especially at the early stage.

Contact

There have been some cases showing a trend toward increasing TPS when the artificial bone has been placed in a manner such that the load could not be borne on the cortical bone, which has greater mechanical strength. Concerning the change of TPS, the contact area shifts to the posterior portion postoperatively and the tensile stress of the anterior cruciate ligament (ACL) increases when the TPS becomes large. The increasing TPS is undesirable in ACL-deficient cases, because it leads to excessive anterior translation and subluxation of the tibia [29]. Furthermore, increasing the TPS may be caused by preoperative contracture or the insufficient detaching of posterior soft tissue during surgery. However, considering the maintenance of the correction angle and early safe weight bearing, the countermeasure regarding strength toward the posterior articular surface and a large gap at the osteotomy portion after the operation was considered to be important factors. These problems will be solved by performing not only a rigid fixation with locking plate system but also the correct placement of artificial bone in the operation. Therefore, the artificial bone should be placed between the stronger sections of the medial and posterior cortical bone (Fig. 4a; Right and 4c). It has been reported that placement between the stronger sections of the medial and posterior cortical bone influence the support of alignment during and after surgery [30]. In this study, retrospective evaluations of imaging studies indicated that there were cases in which the artificial bone was not placed at the posterior cortical bone (Fig. 4a; Left), which has mechanical strength, resulting in the support being provided by cancellous bone. These cases showed a tendency toward an increase in the tilt of the TPS (Table 1c).

Limitation

Limitations of this study include the small number of included patients. Improvements in the use of artificial bone in OWHTO are attempted routinely, and favorable results are being obtained in terms of autologous bone replacement. As a result, there are ethical issues with the use of a treatment group subjected to non-efficient, previously applied methods for comparison.

Conclusions

There are a variety of methods to use artificial bone in orthopaedic surgery. The creation of holes and removal of air in artificial bone are recommended. These surgical techniques are simple and allow for earlier synostosis at the interface between artificial bone and the recipient bone tissue at the early postoperative stage. In OWHTO as well, the surgeon should consider and implement techniques enabling the best results for the intended use in terms of synostosis and mechanical support.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This study was approved by the Institutional Review Board director of National Hospital Organization Nara Medical Centre. The patient provided permission to publish this clinical case, and the identity of the patient has been protected.

Informed consent Informed consent was obtained from all the patients to present their medical data.

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