ORIGINAL ARTICLE

Bone defect reconstruction in children using the induced membrane technique: A series of 14 cases

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KEYWORDS
Bone reconstruction; Children; Induced membrane reconstructive technique

Summary

Introduction: In pediatrics, Masquelet’s induced membrane reconstructive technique has mainly been used in the context of cancer surgery reconstruction or congenital pseudarthrosis of the tibia. This retrospective study consisted of a series of pediatric patients where bone defects were reconstructed with this technique.

Materials and methods: Between 2006 and 2011, 14 children underwent bone reconstruction using this technique in the context of trauma, tumor resection or congenital pseudarthrosis. The mean age was 10.6 years (range: 12 to 17 years) at the time of reconstruction. The length of the defect to be reconstructed relative to the length of the bone (index of reconstruction, expressed as a percentage) and bone healing was evaluated on standard radiographs. Complications were recorded.

Results: The mean index of reconstruction was 32.8% (range: 13.9 to 51%). The mean follow-up was 30 months (range: 1 to 63). Bone union was achieved in 9.5 months (range: 2 to 25). Complications mainly consisted of non-union in 35% of cases, which consolidated after grafting and rigid fixation. Two cases of wound dehiscence were noted. Massive graft resorption occurred in a single case.

Discussion: A technical error was identified in each non-union case (insufficient cement overlap of the bone ends or fixation not stiff enough). These long defects required a large volume of autograft, which constitutes the limiting factor especially in very young children. We used allograft bone chips or a tibial bone strut to increase the graft volume in the largest reconstructions. In this pediatric-only series, an average of one-third of the bone length was successfully reconstructed. Although the technique appears simple, it must be performed rigorously to ensure the cement sufficiently overlaps the bone ends and the defect is properly stabilized to prevent non-union, which is the main complication.

Level of evidence: Level IV (retrospective study).

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Introduction

In 2000, Masquelet [1] described an innovative technique that allowed to be reconstructed in the diaphyseal and metaphyseal regions. This technique is based on the formation of an induced membrane around a polymethylmethacrylate (PMMA) spacer. This membrane prevents graft resorption and secretes growth factors that contribute to bone consolidation [2].

The induced membrane technique has been used to treat septic lower limb non-unions in adults [3,4] and has more recently been used in children to fill bone defects left after tumor resection [5–7] or to address congenital defects. Up to now, it has only been used in congenital pseudarthrosis of the tibia [8–10] and clavicle [11], with two of these cases being ours.

This study consisted of a series of pediatric patients with bone defects resulting from various causes (tumor, congenital, trauma) that were treated with Masquelet’s induced membrane technique.

Material and methods

This was a retrospective, continuous, single-center study involving 14 patients (7 boys, 7 girls) who were treated in our department for a segmental bone defect using the Masquelet technique between 2006 and 2011. The average age was 10.6 years (range: 1–17 years) at the time of the first reconstruction stage. The bone loss was caused by trauma in three cases or was secondary to resection of a malignant tumor in four cases, resection of a benign tumor in three cases and congenital pseudarthrosis in four cases. The size of the bone defect, the bone location and the type of graft were recorded (Table 1).

The bone reconstruction was performed in two separate surgical stages as described by Masquelet [1]. The first stage consisted of inserting a PMMA spacer in the bone defect and using stiff internal or external fixation. The spacer was cast in 50 ml half-syringes that were split longitudinally into two parts and placed in the defect while making sure the bone ends were covered. The syringes were removed once the cement had polymerized and the site was closed. In patients with a lower limb bone defect, weight-bearing was not allowed between the two surgical stages.

In the second stage, 6 to 8 weeks later, the cement spacer was carefully removed. In patients with malignant tumors, the second stage was performed 6 to 8 weeks after the end of the adjuvant chemotherapy. The membrane induced around the cement spacer was opened longitudinally. The cement was broken up and removed, while making sure not to damage the membrane. The bone was decorticated at both ends and then the defect filled with morselized cortical cancellous bone graft. This was an autologous bone graft harvested from one or both posterior iliac crests (depending on the volume needed and if bone had previously been harvested from the iliac crest) with the patient in ventral decubitus. In some cases, additional graft material was needed: morselized cancellous allograft or biphasic calcium phosphate (BCP) as a single-dose when little or no allograft bone chips were available. A tibial bone strut was harvested and added to the graft when more than 40% of the total bone length was being reconstructed. The Reamer-Irrigator-Aspirator (RIA, Synthes) was used once to harvest the graft in a teenage girl with closed growth plates. This technique was used after the remission of the current tumor had been confirmed. The membrane was then sutured and the incision site closed without drains.

Radiological parameters were measured on A/P X-rays of the bone in question once the PMMA spacer had been removed. The Bone Reconstruction Index (BRI) was defined

<table>
<thead>
<tr>
<th>Case</th>
<th>Age (years)</th>
<th>Sex</th>
<th>Bone</th>
<th>Cause</th>
<th>Fixation</th>
<th>Time before grafting (weeks)</th>
<th>Graft</th>
</tr>
</thead>
<tbody>
<tr>
<td>LJI</td>
<td>14</td>
<td>f</td>
<td>Tibia</td>
<td>Trauma</td>
<td>Uniplanar Ex Fix</td>
<td>5</td>
<td>Post. iliac crest</td>
</tr>
<tr>
<td>FE</td>
<td>11</td>
<td>f</td>
<td>Femur</td>
<td>Malignant tumor (ES)</td>
<td>Nail</td>
<td>41</td>
<td>Post. iliac crest</td>
</tr>
<tr>
<td>OA</td>
<td>1</td>
<td>m</td>
<td>Tibia</td>
<td>Congenital</td>
<td>K-wire/cast</td>
<td>6</td>
<td>Post. iliac crest</td>
</tr>
<tr>
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<td>m</td>
<td>Ulna</td>
<td>Benign tumor (HME)</td>
<td>K-wire</td>
<td>6</td>
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</tr>
<tr>
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<td>m</td>
<td>Tibia</td>
<td>Congenital</td>
<td>K-wires</td>
<td>7</td>
<td>Post. iliac crest + BCP</td>
</tr>
<tr>
<td>PJ</td>
<td>16</td>
<td>m</td>
<td>Tibia</td>
<td>Trauma</td>
<td>Uniplanar Ex Fix</td>
<td>6</td>
<td>Post. iliac crest</td>
</tr>
<tr>
<td>BE</td>
<td>7</td>
<td>f</td>
<td>Clavicle</td>
<td>Congenital</td>
<td>K-wire</td>
<td>7</td>
<td>Post. iliac crest</td>
</tr>
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<td>13</td>
<td>f</td>
<td>Femur</td>
<td>Benign tumor (FD)</td>
<td>Nail</td>
<td>6</td>
<td>Post. iliac crest</td>
</tr>
<tr>
<td>FM</td>
<td>14</td>
<td>f</td>
<td>Femur</td>
<td>Malignant tumor (OS)</td>
<td>Plate</td>
<td>34</td>
<td>Post. iliac crest + tibia</td>
</tr>
<tr>
<td>GR</td>
<td>16</td>
<td>m</td>
<td>Humerus</td>
<td>Benign tumor (ABC)</td>
<td>Nail</td>
<td>7</td>
<td>Post. iliac crest + tibia + allograft</td>
</tr>
<tr>
<td>HC</td>
<td>13</td>
<td>f</td>
<td>Femur</td>
<td>Malignant tumor (OS)</td>
<td>Plate</td>
<td>34</td>
<td>Post. iliac crest + tibia + allograft + BCP</td>
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<tr>
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<td>5</td>
<td>f</td>
<td>Fibula</td>
<td>Congenital</td>
<td>K-wire</td>
<td>8</td>
<td>Post. iliac crest</td>
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<tr>
<td>BJJ</td>
<td>12</td>
<td>m</td>
<td>Tibia</td>
<td></td>
<td>Circular Ex Fix</td>
<td>7</td>
<td>Post. iliac crest + BCP</td>
</tr>
<tr>
<td>PP</td>
<td>17</td>
<td>f</td>
<td>Humerus</td>
<td>Malignant tumor (ES)</td>
<td>Nail</td>
<td>36</td>
<td>RIA + allograft</td>
</tr>
</tbody>
</table>

as the length of the bone defect relative to the total length of the involved bone and expressed as a percentage. Bone union was evaluated on A/P and lateral X-rays. The date on which weight-bearing was achieved was recorded for cases involving the lower limb. The follow-up period was determined starting from the second surgical stage. Any complications were noted.

Results

On average, 10.3 cm (range: 3.8—19.2) of the bone length was reconstructed, which corresponded to 32.8% (range: 13.9—51) of the length. In 12 of 14 cases, more than 20% of the bone length was reconstructed. The average follow-up was 30 months (range: 12—63).

The major complications were five cases of non-union, three proximal and two distal. In two of these cases, addition of an autograft led to union. In the three other cases, the fixation was modified: the standard (uniplanar) external fixator was replaced by internal fixation or a circular external fixator. In one of these three cases, this was the second surgical revision—a uniplanar external fixator had initially been used to replace the insufficiently stiff K-wire fixation. One case of massive graft resorption occurred which compromised the reconstruction; it was not taken into account when overall bone union was determined.

The average time to bone union after the second stage was 9.5 months (range 2—25). When looking at each type of pathology, the average time to union was 7.8 months for congenital pseudarthrosis, 8.0 months for benign tumors, 8.3 months for malignant tumors and 15.3 months for traumatic injuries. No fractures occurred in the reconstructed bone. Two cases of wound dehiscence occurred after the grafting (during chemotherapy); these were treated by negative pressure wound therapy (V.A.C.® Therapy system, Kinetic Concepts, USA). There were no infections. The average follow-up after the second stage was 25.7 months (range: 4—63). The results of the entire series are summarized in Table 2.

Discussion

The induced membrane technique developed by Masquelet provides new options for segmental bone defect reconstruction. Its use in trauma cases in children has only been described in one case report on osteitis secondary to pinning of a radius fracture [12], a series of pediatric diaphysis reconstruction where 10 patients were treated with the induced membrane [13] and within a mixed series of adults and children [14]. Two studies have described its use following tumor resection surgery, one multi-center study with 12 patients [6] and one study with eight patients [7]. Our pediatric series is heterogeneous in terms of patient age and indications.

More recently, congenital pseudarthrosis has been treated with the Masquelet technique [8—11], but these were only case reports. Series involving children only have not been published. In the first case reports [8,10] (including one patient in the current series), the time to union was fairly short and ranged from 45 days to 4 months, without any repeated fractures. The preferred age at the time of the procedure is 3 to 5 years old for a vascularized fibula graft [15] and 5 years or older for the Ilizarov method [16]. However, the induced membrane technique can be used in younger patients.

We previously reported on the Masquelet technique being used in one case to treat congenital pseudarthrosis of the clavicle [11], which was included in the current series. This treatment strategy was chosen because of the possibility of non-union or hardware fixation failure had been

<table>
<thead>
<tr>
<th>Case</th>
<th>BD (cm)</th>
<th>BRI (%)</th>
<th>Complications</th>
<th>Surgical revision</th>
<th>Union (months)</th>
<th>Return to weight-bearing (months)</th>
<th>Follow-up (months)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LJ</td>
<td>7.8</td>
<td>22.6</td>
<td>Proximal non-union</td>
<td>K-wires + autograft at 16 months</td>
<td>25</td>
<td>6</td>
<td>63</td>
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<tr>
<td>FE</td>
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<td>33.6</td>
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<td>Autograft at 11 months</td>
<td>13</td>
<td>3</td>
<td>48</td>
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<tr>
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<td>36.9</td>
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<td>N/A</td>
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<td>Autograft at 8 months</td>
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<td></td>
<td>40</td>
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<td>28.7</td>
<td>Proximal non-union</td>
<td>Uniplanar Ex Fix + autograft at 5 months</td>
<td>19</td>
<td>2</td>
<td>28</td>
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<tr>
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<td>29</td>
<td>Proximal non-union</td>
<td>Plate + autograft at 13 months</td>
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<td>1</td>
<td>30</td>
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<tr>
<td>BE</td>
<td>9</td>
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<td>None</td>
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<td>LA</td>
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<td>28.9</td>
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<td>N/A</td>
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<td>2</td>
<td>30</td>
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<tr>
<td>FM</td>
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<td>Wound dehiscence</td>
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<td>6</td>
<td>8</td>
<td>24</td>
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<tr>
<td>GR</td>
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<td>N/A</td>
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<td></td>
<td>20</td>
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<tr>
<td>HC</td>
<td>19.2</td>
<td>48.5</td>
<td>Wound dehiscence</td>
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<td>2</td>
<td>12</td>
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<tr>
<td>NE</td>
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<td>None</td>
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<td>4</td>
<td>3.5</td>
<td>14</td>
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<tr>
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<td>13.9</td>
<td>None</td>
<td>N/A</td>
<td>3</td>
<td>4</td>
<td>15</td>
</tr>
<tr>
<td>PP</td>
<td>13</td>
<td>39</td>
<td>Massive resorption</td>
<td>Waiting period</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

BD: bone defect; BRI: bone reconstruction index; Ex Fix: external fixator; N/A: not applicable.

Table 2  Size of segmental bone defect, bone reconstruction index, complications and time to bone union.
reported [17–19]. The Masquelet technique combines the two main elements needed for bone union — the presence of a membrane that can be absorbed into the periosteum and a cortical-cancellous bone graft.

The Bone Reconstruction Index measured in the current series showed that the technique was used to successfully reconstruct an average of one-third of the involved bone. This large defect requires significant amounts of autograft, which is the limiting factor especially in very young children. To increase the graft volume, we added allograft bone chips to construct a composite graft, but the allograft portion never exceeded 20% of the volume. Masquelet added xenograft and recommended not exceeding 30% of the volume [1]. We empirically chose to reduce the allograft portion in our patients, so the allograft would be completely incorporated once it was mixed with the autograft and the bone marrow released from it (penetration of bone marrow inside the allograft bone trabeculae). If this ratio is exceeded, the allograft is visible, which means that it will not be repopulated as well by the patient’s bone cells.

A cortical autograft (tibia) can also be added to the induced membrane, without its volume hindering the union. This type of construct has been used recently after bone tumor resection [5,6]. We empirically chose to use this cortical autograft for reconstruction of defects with a BRI above 40% (three cases), not only because it increases the graft volume but also because it provides primary stability to the graft. The bone strut was embedded into the two residual bone ends or screwed into the plate when this type of internal fixation method was used (Fig. 1).

Although the Reamer-Irrigator-Aspirator is a promising approach for bone graft harvesting in adults [3,20], it cannot be used in children with open growth plates. We used this type of graft in a mature teenage female patient with closed growth plates, but massive graft resorption occurred, although morselized allograft had been added (Fig. 2). The relationship between RIA and resorption is not clear. Moreover, this graft harvesting technique was not used in the lone resorption case described previously [7].

The Masquelet technique was initially described as a means to fill trauma-induced bone defects, and a wait of 6 to 8 weeks between the two surgery stages was thought to be optimal [1,21]. As in other series [6,7], the second stage was performed 6 to 8 weeks after the last course of adjuvant chemotherapy to help reduce the drug-induced anti-mitotic effect on osteoblasts and improve the neutropenia, which is one of the main factors predisposing the patient to infection. This delay between the two stages is empirical. The results seem to show a satisfactory reconstruction despite this delay in grafting. Nevertheless, the case of massive graft resorption is the only true failure that cannot be explained. One case of complete graft resorption within the induced membrane during reconstruction of a 22 cm defect of the femur during osteosarcoma treatment has been previously reported [7]. Because this type of resorption had previously not been observed, we should be extremely careful going forward. A better understanding of the cellular steps involved in this type of reconstruction (especially osteoclastogenesis inside the membrane) is essential to explain this type of complication and make sure it does not happen again.

![Figure 1](image1.png)

**Figure 1** Reconstruction of 14-cm long segmental bone defect in the metaphysis and diaphysis of the distal femur in the context of osteosarcoma treatment. A. Plate and screw fixation with some of the screws being placed in the void of the future graft area and then insertion of the molds (cut syringes). B. Addition of PMMA to the molds. C. X-rays immediately after the morselized cortical-cancellous bone graft was added and the tibial bone strut was secured to the free screws on the plate. D. X-rays 15 months after the grafting procedure. The femur has healed and the graft has remodeled.

The relative high rate of non-union (five patients in this series or 35%) can be attributed to technical problems each time, as they mainly occurred in our earlier cases (learning curve). In two cases, the cement did not provide sufficient overlap during the first stage. As a consequence, during the second stage, the cortical-cancellous autograft did not cover enough of the bone margins and probably led to the lack of fusion between the newly formed bone and the resected margins (Fig. 3). In the three other cases, we believe the fixation used was not stiff enough. Fixation with a
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uniplanar external fixator was initially used in two cases. In the other case, the initial fixation was made with elastic stable intramedullary nailing (ESIN). Because of the proximal non-union associated with a radiolucent area around the K-wire, the fixation system was changed to a uniplanar external fixator. The lack of healing then led us to replace this uniplanar fixator with a circular external fixator, which finally resulted in union (Fig. 4). Although we cannot draw any statistical conclusions because of the small sample size in the current series, our observations are consistent with Karger’s [14], who found that a circular external fixator is also preferable in children if the bone defect is being stabilized by external fixation. No patient with ESIN had a bone union in the Villemagne series [6].

The non-unions could also be explained by the quality of the reconstructed bone relative to the initial pathology, especially in cases of congenital pseudarthrosis. In the current series, three of the four cases of congenital pseudarthrosis easily achieved bone union; the sole case of non-union was due to the excess motion caused by the ineffective nailing. But only a large-scale study could substantiate these observations.

The observed complications led us to alter our surgical technique during the first stage:

(i) a longer cement sleeve is constructed so that the induced membrane overhangs the resection margins;
(ii) stable fixation is added (ESIN is used when a locking nail is not appropriate and a circular external fixator is preferred to a uniplanar one).

Plate and screw fixation is ideal but can be problematic to perform in small children or when the reconstructed area is near a growth plate. A tibial bone strut is added to the graft when more than 40% of the bone is being reconstructed.

Figure 2  Reconstruction of 13-cm long segmental bone defect in the humerus in the context of Ewing sarcoma. Addition of cement immediately after resection (A), RIA grafting 36 weeks after the resection (B), massive resorption 5 months after the grafting procedure (C).

Figure 3  Reconstruction of 11.5-cm long segmental bone defect in the femur in the context of Ewing sarcoma. Cement added after the resection (A) but does not extend far enough (insufficient overlap) distally (white arrow), which resulted in distal non-union 11 months after the grafting (B); the non-union was treated by bone decortication and grafting and resulted in complete union. Appearance after 4 years of follow-up (C).
Conclusion

Initially used in trauma cases after resection of septic non-unions, then used after resection of malignant tumors, the induced membrane technique allows large segmental bone defects to be reconstructed. The indications have been extended in pediatric orthopedics to the management of congenital pseudarthrosis of the tibia or clavicle. Benign or malignant tumors in children can also be treated with this type of reconstruction. This method is perfectly feasible in children as long as an appropriate fixation method is used and the graft volume is increased as needed, especially in younger children.

In this series of pediatric-only cases, we were able to reconstruct an average of one-third of the length of the involved bone. The relative simplicity of the technique nevertheless requires that a rigorous technique be used, especially in terms of the cement overlap and the stability of the fixation construct. Under these conditions, it may be possible to avoid non-union, which is the primary complication. There is a possibility of graft resorption, but this is not well understood.

Disclosure of interest

The authors declare that they have no conflicts of interest concerning this article.

References


Figure 4  A. Reconstruction of congenital pseudarthrosis of the leg with placement of cement and intramedullary pinning with K-wires. B. Radiolucent area due to unstable K-wire fixation (white arrow) leading to non-union. C. Unstable uniplanar external fixator and non-union after repeated grafting. Implantation of circular external fixator and graft (D) leading to bone union on A/P (E) and lateral (F) X-rays.


