Original Article

Treatment of atrophic femoral non-unions according to the diamond concept: Results of one- and two-step surgical procedure

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ABSTRACT

Background: The treatment of non-unions in long bones poses a great challenge, particularly in cases of infection or large osseous defects. This article evaluates the use of the diamond concept in the treatment of femoral non-unions in a one-step or two-step procedure according to the Masquelet technique.

Patients and methods: Between February 2010 and March 2014, 88 patients with atrophic femoral non-unions were included in our study. The treatment was performed in one step (Group G1) on 41 patients and in two-step Masquelet technique (Group G2) on 47 patients, according to the diamond concept. In 72 cases it was decided to apply the growth factor BMP-7. The mean age of patients was 49.9 ± 15.3 . The data were analysed after following up all patients for at least 12 months after surgery.

Results: 74% of patients achieved consolidation in an average of 9.3 months. Positive bacterial cultures were found in 16 cases (18%). The consolidation rate in G2 was dependent on the non-union localisation and the osteosynthesis method applied. 83% of patients treated by intramedullary reaming achieved consolidation, while this was the case for only 60% of patients with osteosynthesis plates. Smokers in G2 had a larger average osseous defect and a lower consolidation rate. The quality of life as assessed with the SF-12 questionnaire had improved in both groups, with no significant differences between G1 and G2 one year after surgery.

Conclusions: One-step therapy is a suitable method of treatment for aseptic femoral non-unions with small osseous defects, using BMP-7 and RIA in the case of primarily failed atrophic non-union treatment. The Masquelet technique is an efficient means of eradicating infections in non-unions. In combination with intramedullary nailing, this technique is the method of choice for the treatment of femoral shaft non-unions with large defects.

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1. Introduction

The femur is the strongest bone in the human body, and its ability to bear stress is key to a patient's mobility. Subsequent occurrence of delayed union or non-union, with an incidence of 9.3% in recent research, is a serious diagnosis for the affected patients with far-reaching consequences for their everyday lives.¹ Prolonged periods of pain and physical disability, long hospital stays and resultant long-term unemployment all entail financial

disadvantages and a substantial decrease in the quality of life.^{2,3} Femoral non-union, in comparison to tibial non-union, has been shown to result in a particularly high rate of unemployment and early retirement. Mental conditions such as depression may also occur as a consequence of the posttraumatic psychological distress.^{4,5} The treatment of non-union is complex and expensive, placing a burden on the public health system. The costs resulting from the patient's inability to work are relevant to the public economy.^{3,6}

Non-unions involving large osseous defects or infections are particularly problematic.⁷ They may result in repeated unsuccessful treatment, persistent infection, limb-length inequalities and deformity, culminating in the loss of the extremity or, in the course of a septic response, even the loss of life.^{8,9}

A successful therapeutic concept for the effective treatment of impaired fracture healing is the “diamond concept”.^{10,11} This is

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based on five equally important factors: osteogenicity (mesenchymal stem cells), osteoconduction (scaffolds), osteoinduction (growth factors), mechanical stability and vascularity. The diamond concept can be combined with the two-step Masquelet procedure, as we demonstrated for the first time in a clinical study on tibial non-unions.^{12–15}

The goal of this study is to analyse the outcome of femoral non-unions treated according to the diamond concept and to evaluate our one-step and two-step femoral non-union treatment procedures.

2. Patients and methods

Between February 2010 and March 2014, 424 patients with non-unions were treated in our centre. During this period of time we registered 91 patients with atrophic non-unions of the femur with localisation distal to the lesser trochanter who were treated at our clinic according to the diamond concept. Two patients subsequently had to be excluded from our study due to lack of follow-up. One patient opted not to participate.

88 patients met the criteria and were finally included in the study.

41 patients received one-step treatment (Group 1, G1) and 47 patients received two-step treatment according to the Masquelet technique (Group 2, G2). In both groups, bone reconstruction was performed according to the diamond concept principles^{10,11,16} (Fig. 1).

The study did not cover patients with trochanteric non-union or above, since other types of treatment are used in these cases. Further exclusion criteria included an existing pregnancy, legal minority, a malignant tumour undergoing acute treatment, ongoing immune suppression and autoimmune diseases.

2.1. Data collection and analysis

Clinical and radiological parameters were measured preoperatively as well as 4, 6, and 12 weeks and 6 and 12 months postoperatively. The goal of these strict follow-ups was to monitor the success of consolidation, ensure the ongoing medical care of our patients, diagnose possible complications as early as possible and intervene when needed.

In order to measure the subjective health of patients, we used the SF-12 questionnaire both preoperatively and at every follow-up. The patients' subjective contentment with the treatment (0 = very dissatisfied to 10 = very satisfied) was measured with our own questionnaire.

An experienced trauma surgeon analysed all radiological and clinical data 1 year after surgery. The following factors were taken into account:

Fig. 1. The 'diamond concept'.

- Consolidation present in at least 3 of 4 planes.
- Secondary implant loosening.
- Any deviation of the secondary axis.

In addition, the results of the SF-12 questionnaire were evaluated with the help of the scoring sheets provided. To give an accurate overview of the course of healing, we evaluated all questionnaires from before surgery as well as from all follow-up visits after surgery.

2.2. Risk profile

In order to assess the individual risk of a non-union after trauma, we used a scoring system developed by Moghaddam et al.¹⁷ (Table 1). This system includes specific, differently weighted parameters such as the localisation of the fracture, soft tissue damage, smoking status and co-morbidities, which increase the risk of developing a non-union. Patients were grouped as low-risk (score of 0–9), medium-risk (score of 10–20) or high-risk (score >20).

To classify the non-union prior to surgery, we applied the Non-Union Scoring System (NUSS) developed by Calori et al.¹⁸ (Table 2). This system rates the severity of a non-union with a score from 0 to 100, taking 15 factors into account. A score of 0–25 indicates a classic non-union that is likely to heal well with standard treatment. A score of 26–50 calls for a more specialised treatment. Scores of 51–75 indicate a more complex non-union that is unlikely to heal without a highly specialised therapeutic concept. For a score of 76 or more, amputation should primarily be considered, as healing is highly unlikely.

2.3. Indication for treatment

The indication for treatment was determined in accordance with the diamond concept, observing strict criteria.¹⁴ Patients who had osseous defects of less than 2 cm or who were clinically free of

Table 1

Score to estimate the individual risk of patients for delayed union of long bone fractures.¹⁷

Localisation						
Humerus	Prox.	4 points	Diaph.	6 points	Distal	2 points
Forearm	Prox.	4 points	Diaph.	6 points	Distal	2 points
Femur	Prox.	4 points	Diaph.	6 points	Distal	8 points
Tibia	Prox.	6 points	Diaph.	8 points	Distal	4 points
Soft tissue	1° open	4 points	2° open	6 points	3° open	10 points
	Fasciotomy	4 points ^a	Previous fracture	8 points ^a	Neurological disorder	6 points ^b
Smoking	Smoker	15 points	Previous smoker	5 points	Non-smoker	0 points
Comorbidity/medication	NSAID	4 points	Bisphosphonate	6 points	Diabetes	4 points
Type 1			<10 points			Low risk
Type 2			10–20 points			Medium risk
Type 3			>20 points			High risk

^a Affected bone.

^b Affected limb.

Prox, proximal; Diaph, diaphyseal.

Table 2
Non-Union Scoring System.¹⁸

		Score ^a	Max. score
<i>The bone</i>			
Quality of the bone	Good	0	3
	Moderate (e.g. mildly osteoporotic)	1	
	Poor (e.g. severe porosis or bone loss)	2	
	Very poor (necrotic, appears avascular or septic)	3	
Primary injury – open or closed fracture	Closed	0	5
	Open 1° grade	1	
	Open 2–3° A grade	3	
	Open 3° B–C grade	5	
Number of previous interventions on this bone to procure healing	None	1	4
	<2	2	
	<4	3	
	>4	4	
Invasiveness of previous interventions	Minimally invasive: closed surgery (screws, k wires, ...)	0	3
	Internal intramedullary (nailing)	1	
	Internal extramedullary	2	
	Any osteosynthesis which includes bone grafting	3	
Adequacy of primary surgery	Adequate stability	0	1
	Inadequate stability	1	
Weber & Cech group	Hypertrophic	1	5
	Oligotrophic	3	
	Atrophic	5	
Bone alignment	Anatomic alignment	0	1
	Non-anatomic alignment	1	
Bone defect	0.5–1 cm	2	5
	1–3 cm	3	
	>3 cm	5	
<i>Soft tissues</i>			
Status	Intact	0	6
	Previous uneventful surgery, minor scarring	2	
	Previous treatment of soft tissue defect (e.g. skin loss, local flap cover, multiple incisions, compartment syndrome, old sinuses)	3	
	Previous complex treatment of soft tissue defect (e.g. free flap)	4	
	Poor vascularity: absence of distal pulses, poor capillary refill, venous insufficiency	5	
	Presence of actual skin lesion/defect (e.g. ulcer, sinus, exposed bone or plate)	6	
<i>The patient</i>			
ASA grade	1 or 2	0	1
	3 or 4	1	
Diabetes	No	0	2
	Yes – well controlled (HbA1c < 10)	1	
	Yes – poorly controlled (HbA1c > 10)	2	
Blood tests: FBC, ESR, CRP	FBC: WCC > 12	1	3
	ESR > 20	1	
	CRP > 20	1	
Clinical infection status	Clean	0	4
	Previously infected or suspicion of infection	1	
	Septic	4	
Drugs	Steroids	1	2
	NSAIDs	1	
Smoking status	No	0	5
	Yes	5	

^a Higher score implies more difficult to procure union.

infection were treated with the one-step approach (G1). Patients who had an osseous defect of 2 cm and larger or clinical signs of infection (warmth, swelling and redness) were treated with the two-step approach according to Masquelet (G2). Patients with intraoperative findings that suggested an infection required a change in methods from a one-step to a two-step procedure (Fig. 2).

2.4. Surgical treatment

2.4.1. Pre-surgical care

Besides general surgical preparation, every patient received an X-ray of the lower leg with the adjacent joints in two planes. When using the Reamer-Irrigator-Aspirator™ (RIA) technique, an X-ray of the ipsi- or contralateral femur was taken. A CT scan and a dynamic contrast-enhanced MRI of the lower leg were optional imaging methods for controlling the status of vascularisation.

Fig. 2. Diagram for treatment decision.

- Debridement
- Surgical wound sanitation
- Osteosynthesis
- Defect filling with PMMA-cement with vancomycin:
 - ✓ Eradication of possible infection
 - ✓ Induction of a Masquelet membrane

a: Cement spacer forming

b: Plate osteosynthesis and cement spacer implant

Fig. 3. Masquelet step I.

2.4.2. Masquelet technique (G2)

Treatment according to the Masquelet technique comprises two operations at an interval of 6–8 weeks.

In a first step, previously implanted osteosynthesis material is completely removed, the proximal and distal ends of the non-union gaps are debrided down to healthy bone, and cement with antibiotics (PMMA) is implanted in the defect to induce a Masquelet membrane and start an effective osteitis therapy. Finally, a reosteosynthesis is performed to ensure optimal stability (Fig. 3).

After approximately six weeks a Masquelet membrane has formed around the spacer. Any remaining infection of the non-union must be completely cured before the next stage of therapy. If this is not the case, the first step is repeated as often as necessary, replacing the cement spacer each time.^{12,13}

2.4.3. Filling the defect (G1 + G2)

When there is no further sign of infection, the second stage of therapy can take place. The cement spacer is removed, leaving the membrane in place, and the bone defect is filled with a cancellous bone graft taken from either the iliac crest or – using the Reamer-Irrigator-Aspirator™ (RIA) – from the contralateral femur. Depending on the classification of the non-union, the diamond concept may indicate the use of tricalcium phosphate (Vitoss™) and off-label use of BMP-7 (Eptotermin alfa, Osigraft®).¹⁹ This second step of surgery could also include an optimisation of the osteosynthesis if necessary (Figs. 4 and 4).

2.4.4. One-step procedure (G1)

The gold standard of atrophic non-union treatment is the use of cancellous autograft material. Additional treatment with growth

When infection status is negative:

- Removal of the cement spacer
- If necessary optimisation of biomechanical stability
- Defect filling

a: RIA procedure on contralateral femur

b: RIA

c: Combination of RIA, BMP-7, autologous bone graft (iliac crest)

Fig. 4. Masquelet step II.

Fig. 5. Sample patient (♀, 50 yrs) treated in Masquelet technique according to the diamond concept principles.

factors is required after failure of the first attempt at treating the non-union. In all other respects, the surgical procedure is identical to the second step of the Masquelet technique.

2.5. Statistical methods

Statistical analysis was performed under the guidance of the Institute for Medical Biometrics and Informatics of the University of Heidelberg, Germany. The statistical analysis and creation of tables were performed using SPSS 21.0 (IBM® Deutschland GmbH), Excel® 2010 and Word® 2010 (Microsoft®). Continuous

data were expressed as mean values, standard deviation, minimum and maximums; categorical data were expressed as absolute and relative frequencies. Any differences between groups in continuous data were evaluated with the student *t*-test, with the Chi-square test in case of categorical data. Differences in the course of healing were examined with the student *t*-test for dependent variables. The level of significance (α) was set at 5%.

The study was executed in concordance with the Declaration of Helsinki. Approval was received from the ethics commission of the Medical Faculty of the University of Heidelberg (S-532/2011).

3. Results

3.1. Patient characteristics

The ratio of male and female patients in our collective ($n = 88$) was well balanced at 43–45 (49–51%). At the time of surgery, our patients were an average of 49.9 ± 15.3 years old. An average of 26.6 ± 31.7 months elapsed from trauma to non-union surgery at our clinic. The average bone defect size after resection was 3.0 ± 3.5 cm. The patients had an average of 2.9 ± 2.8 previous surgeries.

In 61 cases the fracture that led to non-union was caused by a trauma such as a road accident or a fall, and in 12 cases a corrective osteotomy of the femur resulted in a non-union. The remaining 15 cases could be attributed to a variety of causes.

Additional data concerning patient and non-union characteristics are listed in Tables 3 and 4.

3.2. Details of surgery

The uneven distribution of distal and diaphyseal non-unions in G1 and G2 and the resultant osteosynthesis procedures gave rise to a significant difference between the procedures applied within each group in our collective. In G1 ($n = 41$) there was a greater proportion of diaphyseal non-unions (30 cases, or 73%). Intramedullary osteosynthesis was therefore the preferred procedure in this group. In G2 ($n = 47$), which showed a greater proportion of distal non-unions (26 cases, or 55%), a new osteosynthesis with a plate was performed on 30 patients, while in five cases the existing osteosynthesis plate was left in place.

72 patients received a combination of cancellous autograft, growth factors (BMP-7) and tricalcium phosphate. In 13 patients

the single use of cancellous autograft was sufficient, and in 3 cases only osteosynthesis was performed (Table 5).

3.3. Risk profile of the collective

Patients were classified into three groups according to the score developed by Moghaddam et al. for determining the individual risk of delayed union or non-union after a fracture. In the overall collective 19 patients (22%) were classified as 'low-risk', 36 (41%) as 'medium-risk' and 33 patients (38%) as 'high-risk'. The average score of all patients was 17.4 ± 8.8 . This score revealed no significant difference between the two groups.

The NUSS score for classifying non-unions according to their need for specialised treatment produced an average value of 43.5 ± 11.8 . There was a highly significant difference between G1 (38.1 ± 9.3) and G2 (48.1 ± 11.9) ($p < 0.001$), as well as in the categorisation of patients. Three patients' score was between 0 and 25 (3%), 64 patients lay between 26 and 50 (73%) and 21 patients had a score between 51 and 75 (24%). There were no patients in the collective scoring between 76 and 100, as these patients are not treated according to the diamond concept but are initially provided with an endoprosthesis or undergo an amputation (Table 6).

3.4. Results of proper bone healing

We achieved bone consolidation meeting the specified criteria in 69 patients (78.4%) out of our overall collective ($n = 88$). 64 of these patients (72.7%) healed without any further surgical intervention, two patients underwent another operation at an early stage due to mechanical irritation of the osteosynthesis, and

Table 3
Patient characteristics.

Characteristic	Total <i>N</i> = 88		One-step (G1) <i>N</i> = 41 (46.6%)		Masquelet (G2) <i>N</i> = 47 (53.4%)		<i>p</i> value
Gender							0.401
Male	43	(48.9%)	22	(53.7%)	21	(44.7%)	
Female	45	(51.1%)	19	(46.3%)	26	(55.3%)	
Age (years)	49.9	± 15.3 (19–83) ^a	44.3	± 15.2 (19–76) ^a	54.7	± 13.7 (31–83) ^a	<0.001 [*]
BMI	28.7	± 6.5 (17.2–46.5) ^a	26.2	± 5.7 (17.2–45.2) ^a	30.5	± 6.4 (20.6–46.5) ^a	0.005 [*]

^{*} Indicates significant differences between the groups; level of significance α was set to 5%.

^a Average $\pm$ standard deviation (minimum–maximum).

Table 4
Non-union characteristics.

Characteristic	Total <i>N</i> = 88		One-step (G1) <i>N</i> = 41 (46.6%)		Masquelet (G2) <i>N</i> = 47 (53.4%)		<i>p</i> value
Location							0.007 [*]
Diaphyseal	51	(58.0%)	30	(73.2%)	21	(44.7%)	
Distal	37	(42.0%)	11	(26.8%)	26	(55.3%)	
Type of fracture							0.497
Closed	70	(79.5%)	33	(80.5%)	37	(78.7%)	
Open 1°	1	(1.1%)	0	(0.0%)	1	(2.1%)	
Open 2°	9	(10.2%)	5	(12.2%)	4	(8.5%)	
Open 3°	8	(9.1%)	3	(7.3%)	5	(10.6%)	
Fracture age (months)	26.6	± 31.7 (3–221) ^a	27.6	± 30.7 (3–181) ^a	25.7	± 32.8 (6–221) ^a	0.785
Previous surgeries (number)	2.9	± 2.8 (1–17) ^a	2.4	± 1.4 (1–7) ^a	3.4	± 3.5 (1–17) ^a	0.128
Bone defect (cm)	3.0	± 3.5 (0.1–18) ^a	1.1	± 0.8 (0.1–5) ^a	4.8	± 3.9 (0.5–18) ^a	<0.001 [*]
Initial osteosynthesis							
External fixation	18	(20.4%)	8	(19.5%)	10	(21.2%)	
Osteosynthesis plate ^b	40	(45.5%)	14	(34.1%)	26	(55.3%)	
Intramedullary nail ^b	32	(36.4%)	20	(48.8%)	12	(25.5%)	
Wire osteosynthesis ^c	4	(4.5%)	1	(2.4%)	3	(6.4%)	

^{*} Indicates significant differences between the groups; level of significance α was set to 5%.

^a Average $\pm$ standard deviation (minimum–maximum).

^b Two patients had been provided with both plate and nail osteosynthesis, one in each group.

^c Was performed additionally.

Table 5
Surgery details.

Characteristic	Total		One-step (G1)		Masquelet (G2)		p value
	N = 88		N = 41 (46.6%)		N = 47 (53.4%)		
Osteosynthesis in domo							0.001 ⁺
Osteosynthesis plate	44	(50.0%)	14	(34.1%)	30	(63.8%)	
Intramedullary nail antegrade	32	(36.4%)	21	(51.2%)	11	(23.4%)	
Intramedullary nail retrograde	7	(8.0%)	6	(14.6%)	1	(2.1%)	
No change ^a	5	(5.7%)	0	(0.0%)	5	(10.6%)	
Surgical procedure							0.026 ⁺
Bone graft + BMP-7	72	(81.8%)	29	(70.7%)	43	(91.5%)	
Bone graft	13	(14.8%)	9	(22.0%)	4	(8.5%)	
No graft	3	(3.4%)	3	(7.3%)	0	(0.0%)	

^{*} Indicates significant differences between the groups; level of significance α was set to 5%.

^a Osteosynthesis plates were left in place in all cases.

Table 6
Risk profile.

Characteristic	Total		One-step (G1)		Masquelet (G2)		p value
	N = 88		N = 41 (46.6%)		N = 47 (53.4%)		
Non-union risk score	17.4	±8.8 (4–43) ^a	16.1	±9.0 (4–43) ^a	18.5	±8.6 (4–37) ^a	0.129
Risk category							0.476
‘Low risk’	19	(21.6%)	11	(26.8%)	8	(17.0%)	
‘Medium risk’	36	(40.9%)	15	(36.6%)	21	(44.7%)	
‘High risk’	33	(37.5%)	15	(36.6%)	18	(38.3%)	
NUSS score	43.5	±11.8 (22–74) ^a	38.1	±9.3 (22–64) ^a	48.1	±11.9 (30–74) ^a	<0.001 [*]
NUSS category							<0.001 [*]
Category 1 (score of 0–25)	3	(3.4%)	3	(7.3%)	0	(0.0%)	
Category 2 (score of 26–50)	64	(72.7%)	35	(85.4%)	29	(61.7%)	
Category 3 (score of 51–75)	21	(23.9%)	3	(7.3%)	18	(38.3%)	
Category 4 (score of 76–100)	0	(0.0%)	0	(0.0%)	0	(0.0%)	
Smoking status							0.227
Smoker	29	(33.0%)	11	(26.8%)	18	(38.3%)	
Former smoker	50	(56.8%)	26	(63.4%)	24	(51.1%)	
Non-smoker	9	(10.2%)	4	(9.8%)	5	(10.6%)	
Diabetes mellitus	9	(10.2%)	3	(7.3%)	6	(12.8%)	0.400

^{*} Indicates significant differences between the groups; level of significance α was set to 5%.

^a Average $\pm$ standard deviation (minimum–maximum).

three patients achieved consolidation after dynamisation of the intramedullary nail to stimulate bone healing.

In collective G1, consolidation took place in 95.1% of cases (39 of 41) while in G2 the consolidation rate was 63.8% (30 of 47). There was no difference in the time that elapsed from the operation (Step 2 for group G2) to the establishment of bone consolidation, averaging 9.3 ± 5.4 months for G1 and 9.4 ± 4.9 months for G2.

For the 19 patients whose non-unions did not heal, the outcome was as follows: Non-union persists in eight patients, one of whom is free of pain and refuses to undergo any further surgery. Five patients finally underwent endoprosthetic surgery after several failed treatments. Six patients achieved consolidation after revision surgery according to the diamond concept.

3.5. Results of the SF-12 questionnaire

The SF-12 questionnaire measures the subjective physical and mental health of the patient. In our overall collective the average physical health value (Physical Component Summary, PCS) rose from 27.9 ± 5.5 before surgery to 33.5 ± 10.6 one year after surgery. The average value in G1 was higher than in G2 in both cases, with a significant preoperative difference. The mental score (Mental Component Summary, MCS) rose significantly from 44.2 ± 12.0 to 48.3 ± 12.3 . There were no significant differences between the two groups (Table 7).

3.6. Specifics depending on non-union localisation

3.6.1. Femoral diaphysis

Healing took place in 84% of diaphyseal non-unions, with a rate of 93% in G1. Only two diaphyseal non-unions in G1 treated with osteosynthesis plates failed to consolidate. These patients were female and the defect was ≥ 2 cm in both cases.

The rate of consolidation in G2 was 71%. Patients who were provided with an intramedullary osteosynthesis achieved a consolidation rate of 91% (10 out of 11). The use of plate osteosynthesis only led to consolidation in 50% of cases (5 out of 10).

An interesting finding in these diaphyseal patients with no consolidation in G2 was that all six were smokers.

3.6.2. Distal femur

The overall healing rate for the distal non-unions was 70%. Whilst all 11 patients in G1 achieved consolidation (100%), G2 had the lowest consolidation rate (15 out of 26, or 58%) in our entire collective.

Almost all patients in G1 (10 cases) and the majority of G2 patients (81%) were treated with osteosynthesis plates. In four cases an existing osteosynthesis plate was left in place, and in one case intramedullary nailing was performed. 67% of patients (14 out of 21) with a new osteosynthesis plate experienced consolidation while only one of the other patients (20%) successfully healed.

Table 7

Outcome characteristics.

Characteristic	Total		One-step (G1)		Masquelet (G2)		p value
	N = 88		N = 41 (46.6%)		N = 47 (53.4%)		
Consolidation							<0.001 [*]
Yes	69	(78.4%)	39	(95.1%)	30	(63.8%)	
No	19	(21.6%)	2	(4.9%)	17	(36.2%)	
Time to heal	9.3	±5.1 (2–32) ^a	9.3	±5.4 (2–32) ^a	9.4	±4.9 (3–21) ^a	0.900
Non-consolidation outcome							
Consolidation after revision surgery	6		2		4		
Endoprosthesis	5		0		5		
Non-union persistence	8		0		8		
SF-12							
PCS							
Preoperative	27.9	±5.5 (17.0–47.1) ^a	30.1	±5.3 (17–36.9) ^a	26.9	±5.5 (19.7–47.1) ^a	0.018 [*]
1 year post op	33.5	±10.6 (14.0–58.8) ^a	36.8	±11.0 (17.4–58.8) ^a	31.3	±9.8 (14.0–50.0) ^a	0.090
Significance within group		0.057		0.084		0.299	
MCS							
Preoperative	44.2	±12.0 (27.1–67.1) ^a	46.4	±12.1 (29.4–62.2) ^a	43.1	±12.1 (27.1–67.1) ^a	0.436
1 year post op	48.3	±12.3 (23.6–69.2) ^a	48.7	±11.0 (28.2–64.0) ^a	48.0	±13.2 (23.6–69.2) ^a	0.948
Significance within group		0.001 [*]		0.026 [*]		0.021 [*]	
Contentment							
Total	7.4	±2.6 (0–10) ^a	8.5	±1.7 (5–10) ^a	6.8	±2.8 (0–10) ^a	0.075
Consolidated patients	8.0	±1.9 (4–10) ^a	8.5	±1.7 (5–10) ^a	7.8	±2.0 (4–10) ^a	0.185

^{*} Indicates significant differences between the groups; level of significance α was set to 5%.^a Average $\pm$ standard deviation (minimum–maximum).

Three of the 11 patients who failed to achieve consolidation were smokers. The average bone defect (3.9 cm) in this group was actually smaller than for the diaphyseal Masquelet patients (5.9 cm).

3.7. Factors affecting consolidation

3.7.1. Smoking status

One-third of our collective were active smokers (29 out of 88 cases). These patients achieved a consolidation rate of 66% and accounted for more than half of the unsuccessful treatments (10 out of 19 cases of failed therapy). While 10 out of 11 smokers (91%) in G1 achieved consolidation, only 50% (9 out of 18) of patients in G2 who were smokers did so.

There was also a correlation between smoking and the size of the osseous defect. The defect was more than twice as long in the smokers (Φ 5.0 cm) as in the non-smokers (Φ 2.1 cm). In G2 the average osseous defect was as long as 7.2 cm compared to an average of 3.3 cm among the non-smokers.

Taken in conjunction with intramedullary osteosynthesis, smoking resulted in a consolidation rate of 92%, while only 47% of smokers healed when an osteosynthesis plate was used. Considering G2 alone, a 75% consolidation rate was achieved among smokers treated with intramedullary osteosynthesis, compared to only 43% of those treated with an osteosynthesis plate.

3.7.2. Size of defect

According to the treatment indication the average osseous defect in G1 was 1.1 cm. Patients treated for diaphyseal non-union showed an average defect of 1.2 cm and those treated for distal non-union an average defect of 0.7 cm. In G2 the average osseous defect was 4.8 cm, 5.9 cm for diaphyseal and 3.9 cm for distal non-unions.

All 45 patients (100%) with an osseous defect <2 cm fully healed. Of the 22 patients with a defect <5 cm, 59% consolidated. 21 patients had a defect of 5 cm or more. The consolidation rate in this group was 52%.

3.7.3. Gender of patient

Of the 43 male patients in our collective, 35 (81%) healed. In the two groups, consolidation occurred in 22 out of 22 male patients

(100%) in G1 and in 13 out of 21 (61%) in G2. Of the total of 45 women, 34 (76%) achieved consolidation. In G1, 17 of the 19 female patients (90%) were healed, and in G2 the number was 17 out of 26 (65%).

3.7.4. Risk assessment (NUSS)

Consolidation occurred in all seven of the NUSS Category 1 patients (100%, all G1), and in 51 out of 61 (84%) Category 2 patients. 12 out of 20 (60%) patients in Category 3 achieved consolidation.

3.8. Microbiological status

In our collective, we found positive bacterial cultures in the intraoperatively removed tissues in a total of 16 cases (18%). The frequency of infection differed between G1 and G2 (6 infections in G1, 10 in G2). The bacterial spectrum covered 10 different bacteria, a contamination with staphylococcus epidermidis being found most frequently (five cases). In most cases there were no clinical signs of infection. All six patients in G1 with a low-grade infection of this kind nevertheless achieved consolidation. Two of these patients were treated postoperatively with antibiotics.

Eight of the 10 patients in G2 were successfully cured of an infection by applying step 1 of the Masquelet technique. Ultimately, even the other two patients were cured of an infection by using this technique during revision surgery. In one case this took place as part of a repeated Masquelet treatment, and in the other case the antibiotic-impregnated cement spacer was implanted in preparation for the provision of an endoprosthesis (Table 8).

3.9. Rate of complications

33 patients (38%) suffered a total of 35 complications over the course of recovery. 8 complications occurred in G1 and 27 in G2. The differing incidence between the two groups was highly significant.

Amputation of a limb was regarded as a major complication. This did not occur in either group. There was a wide range of minor complications, which are listed in Table 9.

Table 8

Bacterial status.

Bacterial spectrum	Total		One-step (G1)		Masquelet (G2)		p value
	N = 88		N = 41 (46.6%)		N = 47 (53.4%)		
Total	16	(18.2%)	6	(14.6%)	10	(21.3%)	0.420*
<i>Staph. epidermidis</i>	5		1		4		
<i>Staph. hominis</i>	2		1		1		
<i>Staph. capitis</i>	2		1		1		
<i>Staph. aureus</i>	1		0		1		
<i>Staph. caprae</i>	1		1		0		
<i>Staph. cohnii</i>	1		1		0		
<i>Enterobacter cloacae</i>	1		0		1		
<i>Streptococcus parasanguinis</i>	1		0		1		
<i>Propionibacterium acnes</i>	1		1		0		
<i>Enterococcus faecium</i>	1		0		1		

* Indicates significant differences between the groups; level of significance α was set to 5%.**Table 9**

Complications.

Complication	Total		One-step (G1)		Masquelet (G2)		p value
	N = 88		N = 41 (46.6%)		N = 47 (53.4%)		
Total ^a	35	(39.8%)	8	(19.5%)	27	(57.4%)	<0.001 [*]
Persisting non-union	8	(9.1%)	0	(0.0%)	8	(17.0%)	
Material failure	11	(12.5%)	2	(4.9%)	9	(19.1%)	
Disorder in wound healing	3	(3.4%)	0	(0.0%)	3	(6.4%)	
Spacer replacement	3	(3.4%)	0	(0.0%)	3	(6.4%)	
Dynamisation	4	(4.5%)	3	(7.3%)	1	(2.1%)	
Revision due to mechanical irritation	2	(2.3%)	2	(4.9%)	0	(0.0%)	
RIA complications	1	(1.1%)	0	(0.0%)	1	(2.1%)	
Other	3	(3.4%)	1	(2.4%)	2	(4.3%)	

* Indicates significant differences between the groups; level of significance α was set to 5%.^a Some patients had more than one complication.

4. Discussion

The goal of our study was to validate our treatment of femoral non-union distal to the lesser trochanter according to the diamond concept. The surgical treatment of patients with a small bone defect and no infection was performed in one step (G1), while patients with a larger defect size and/or clinical signs of infection were treated using the two-step Masquelet technique. The consolidation rate was found to be 95% in G1 and 64% in G2.

The major strength of our study was that patients were both treated and followed up at one centre, so that the same conditions applied for all. We were able to observe a high percentage (97%, or 88 out of 91) of potential patients for our study post-operatively over the course of their recovery. A weakness of this study was the absence of randomisation in group distribution. This was not possible due to the criteria applied in deciding on the most suitable treatment procedure.

4.1. Patient collective

The patients in G2 are those with the worse clinical picture. Besides the selection criteria (size of defect, existence of an infection), the age and BMI of these patients was significantly greater than that of patients in G1. Their higher risk is especially emphasised by the NUSS score, which indicates the likelihood of recovery relative to the severity of osseous non-union: the highly significant different average scores ($p < 0.001$) of 36.1 in G1 and 47.3 in G2 reflect the differing starting positions of patients in the two groups.

4.2. Consolidation

4.2.1. Consolidation in one-step treatment (G1)

The indication for the one-step treatment was based on the absence of clinical signs of infection and an osseous defect smaller

than 2 cm. This type of treatment (G1) produced a high consolidation rate, with only two consolidation failures. Both of these were non-unions of the femoral shaft and had been fixed with an osteosynthesis plate. However, the gold standard in treating fractures of the femoral shaft is antegrade reamed intramedullary nailing.^{20–23} Consequently, a change in procedure from osteosynthesis plate to intramedullary nailing led to consolidation in both cases. A treatment using the Masquelet technique might otherwise have been advantageous, since the osseous defect was ≥ 2 cm in both patients. In that case we would have achieved a consolidation rate of 100% for the one-step method.

Similar results for one-step treatment are reported by Hierholzer et al., who achieved a consolidation rate of 98% in 72 patients with aseptic femoral non-unions treated with reamed intramedullary nailing.²⁴ Megas et al. observed a consolidation rate of 100% when treating non-unions of the femoral shaft by intramedullary nailing.^{25,26} Numerous other authors have in recent years reported similar consolidation rates when using exchange nailing in aseptic non-unions of the femoral shaft.^{27–29} In contrast to our collective, these studies consisted mainly of hypertrophic non-unions and needed no highly specialised treatment.

As a consequence the time to heal in G1 is slightly longer than in these studies. This might also be due to the greater age of our patients (Φ 44.3 years, compared to Φ 33.7 years in Megas et al.). Otherwise it may just be based on inaccuracy of measurement due to the broad interval of between 6 and 12 months with no follow-up appointment.

It is interesting that bone consolidation was not negatively affected by the previously undetected low-grade infections present in this group. An investigation of the treatment of tibial non-unions at our clinic produced the opposite result. In this case, consolidation following one-step treatment was found to be impaired by low-grade infections.¹⁴

4.2.2. Consolidation in two-step treatment (G2)

We performed the surgical two-step Masquelet procedure (G2) for patients with osseous defects of 2 cm and larger or clinical signs of infection.

A differentiated view of the circumstances yields somewhat ambivalent results. Patients with diaphyseal non-union vastly benefited from treatment using intramedullary nailing, whereas treatment with osteosynthesis plates did not meet our expectations. We assume that plate fixation somehow inhibits the vascularity of the femoral shaft, so that insufficient vascularisation of the inserted graft material leads to non-consolidation. This situation indeed occurs in patients with a positive smoking status, where vascularity is particularly poor. Accordingly, this combination produced a high therapy failure rate in our collective. The size of the bone defect, which was particularly large in smokers, undoubtedly also contributed to the failure of treatment. However, there is reason to suppose that this too is caused by smoking, which thus jeopardises the patient's chances of recovery both directly (compromised blood supply) and indirectly (through the size of the bone defect). Like other researchers, we had already established the negative effect of smoking on bone healing in another study investigating tibial shaft fractures.^{17,30,31}

Regardless of these considerations, nearly all patients – including smokers – were fully healed (91%, or 10 out of 11) when intramedullary nailing was used. This leads us to the conclusion that patients with non-union of the femoral shaft should preferably be treated by reamed intramedullary nailing wherever possible.

The most commonly used alternative for the treatment of both aseptic and septic non-unions of the femoral shaft with large sized defects is segment transport based on the Ilizarov technique, which delivers good results in terms of its consolidation rate (86–100%).^{5,32} It is, however, a very protracted and painful technique with a high incidence of complications. Furthermore, it often requires multiple additional operations and does not rectify leg length discrepancies in most cases.^{33–36} Acute shortening and subsequent re-lengthening may produce equally good results in a shorter time with fewer complications. This technique is limited to smaller diaphyseal defects, though, as the greater compression of soft tissue in large defects causes tissue buckling and compromises distal blood flow.³⁷ Saleh and Rees compared the two techniques and recommended the use of acute shortening for defects of less than 5 cm in femoral non-unions.³⁶ The use of a monolateral external distractor shows good results in young patients and also entails fewer drawbacks.³⁸

Regardless of smoking status, the treatment of distal non-unions in G2 was the area which our study found to have the lowest recovery rates. The Masquelet technique is not able to produce the desired success in these cases. Here too, a positive smoking status correlated with a slightly slower consolidation rate and a longer average osseous defect. Nevertheless, there is no obvious connection with regard to the consolidation of distal femoral non-unions, as most of the patients with failed treatment were non-smokers. Our observation of patients with large osseous defects (5–10 cm) revealed that consolidation could only be achieved if the defect did not extend across the entire diameter and an osseous bridge was still present. A possible reason could be the poor vascularity associated with an enlarged bone diameter of the distal femur opposite the diaphysis. The inserted Masquelet material could be too voluminous in such cases, impeding the bone reconstruction. Another possible cause might be that the healing process takes too much time, resulting in diminished stability of the osteosynthesis. In this case the problem could be solved with a more stable osteosynthesis, either using a VA-LCP condylar plate instead of a LISS plate or using dual plate osteosynthesis. Whatever the cause, the Masquelet technique should not be used on the distal femur as the prospects of healing are low.

There are few other options described in literature for treating large osseous defects in distal femoral non-unions. For aseptic non-unions with large defects, decortication is a possible alternative to the Masquelet technique.^{39,40} A further alternative technique is vascularised bone grafting (e.g. using vascularised fibula). This produces good results, but is a demanding procedure that requires microsurgical techniques.^{26,41} A combination with an Ilizarov external fixator has also been shown to produce good results. Lai et al. reported its successful application on five young patients with very large osseous defects in distal femoral non-unions (Φ defect size 15.8 cm).⁴² Since we found that it was particularly the large defects that failed to consolidate, this method is another possible alternative treatment technique. Again, distraction osteogenesis may be a valuable alternative for the treatment of juxta-articular non-unions.⁴³

Nevertheless, the use of the Masquelet technique in G2 proved effective in eliminating all bacterial infections from diaphyseal and distal non-unions of the femur. It may therefore still be useful to apply the first step of the Masquelet procedure in preparation for supplying a prosthesis.

4.3. SF-12 Questionnaire

The values for the healthy German population, with an MCS of 52.2 ± 8.1 and a PCS of 49.0 ± 9.4 , may serve as a reference.⁴⁴

The SF-12 values for our collective one year after surgery are almost identical to the values reported by Zeckey et al. as the outcome of a non-union of the femoral shaft (MCS 49.4 ± 14.0 , PCS 33.9 ± 10.9), as well as to the values for the German norm sample with disability of the limbs (MCS 48.9 ± 10.0 and PCS 34.9 ± 9.7).⁴⁴ Zeckey et al. compared the outcomes of tibial and femoral non-unions and reached the conclusion that the psychological outcome was comparable in both groups, but that the femoral non-union patients were physically restricted to a greater extent.⁴ These findings were confirmed by our own in-house study of the outcome of tibial non-union treatment, where the readings were MCS 50.9 ± 10.7 and PCS 37.5 ± 8.9 .¹⁴

5. Conclusion

The diamond concept is an effective method for the treatment of femoral non-union. To ensure the success of treatment, it is essential to undertake a precise classification of the non-union and to select the type of surgical procedure accordingly. Our results show that patients with atrophic non-unions, with osseous defects of less than 2 cm that are aseptic or have only a low-grade infection achieve excellent healing. For more complex non-unions with large osseous defects or where an infection is present, the use of the Masquelet technique in the femoral shaft is very reliable in conjunction with an intramedullary osteosynthesis.

On the other hand, the Masquelet technique does not produce satisfactory results in the treatment of distal femoral non-unions, and alternative methods of treatment are called for. Even in these cases, however, the first step of the Masquelet procedure is a suitable means of curing an infection and can continue to be used in preparation for the provision of an endoprosthesis.

Conflicts of interest

The authors have none to declare.

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