OPEN

Bone Transport With Internal Devices

Ulrik Kähler Olesen, MD and John E. Herzenberg, MD, FRCSC†*

Summary: Bone defects on a traumatic, infectious or malignant background are effectively treated by distraction osteogenesis with internal bone transport nails, improving patient comfort, reducing treatment time, and minimizing complications during a treatment course that has traditionally been long and burdensome. This article describes a patient selection, indications, devices, techniques, complications, and our suggested treatment protocol. The nails allow for combinations of transport and lengthening, avoiding the use of external fixators and their inherent drawbacks: pin track infection, scarring, and the inconvenience of carrying an external device for a prolonged time. Modern implants allow full weight-bearing during treatment. Meticulous surgical planning, infection prophylaxis, healthy soft tissues, vigorous training, and rehabilitation are essential for good outcomes.

Key Words: bone transport—distraction osteogenesis—lengthening nails—fitbone—precice—bone—tumor.

(*Tech Orthop* 2020;35: 219–224)

Motorized internal bone transport devices were first described by Baumgart, Betz and collegues in the English literature in 1997.[1] However, further development and widespread use of bone transport nails have been challenging due to many factors: limited number of patients, market restrictions, relatively high implant costs—and the fear of infection with internal fixation in complex fractures. Recently, improved availability, technical advancements, and a better understanding of biofilm formation and infection prophylaxis have encouraged a broader market.[2–4]

Bone transport nails have reduced treatment time and complications and facilitated normal daily life during a treatment course that has traditionally been long, costly, and burdensome, in particular for larger defects treated in external ring fixators[4–6]—for an open tibial fracture with bone loss treated with external fixation, more than a year of absenteeism from the workforce is not uncommon.[7]

This article describes, through clinical examples and illustrations, 2 techniques for internal bone transport and their variations, including tips and tricks, and our suggested treatment protocol.

INDICATIONS

Our protocol suggests internal bone transport for defects over 3 to 4 cm in the tibia and over 4 to 6 cm in the femur. In smaller defects, we shorten the segment acutely over a plate and lengthen the bone through a separate osteotomy, sparing the docking procedure.[8,9]

For larger defects (10 cm and up), we recommend shortening, transport, and secondary lengthening. As a rule of thumb, we seek to avoid regenerates over 10 cm (Fig. 1). In traumatic cases with condylar involvement, or in very short articular segments and in large defects, a supplemental locking plate can enhance the construct stability, a technique often referred to as "Plate-assisted Bone Segment Transport (PABST)."[10]

Trauma Considerations

Infection control is mandatory after open fractures. A supplementary plastic surgical surgery procedure is often needed to cover a soft tissue loss in combination with the orthopedic reconstruction, in particular in the tibia. We generally wait up to 6 weeks from the injury and use local (pasta, sponges, pellets) and systemic antibiotics to prevent biofilm formation and secondary deep infection.[11,12] In distal tibial injuries with severe soft tissue loss, the traditional ring fixation remains the treatment of choice in our practice. The femur is relatively more forgiving due to the abundant soft tissue.

In nonunions with suspected infection, in bone loss after previous osteomyelitis, all implants and all devitalized tissue must be removed before initiating internal bone transport, preferably with negative cultures.

Tumor Considerations

In extra-articular malignant cases, with solitary lesions (eg, primary sarcomas or solitary metastatic disease) and occasionally benign conditions (eg, adamantinomas), bone transport is an attractive alternative to traditional endoprosthetic treatment. This accounts especially in younger patients with a remaining life expectancy that justifies a biological reconstruction, which preserves the native joint, potentially preventing multiple future arthroplasties. Concomitant lesions in the same segment must be excluded and the patient should be off radiation-therapy and chemotherapy, to ensure healthy regenerate formation.[13,14] Expanding prostheses that incorporate a distraction nail to compensate for femoral bone growth have been developed to prevent limb length discrepancies after knee replacement, typically in juvenile intra-articular sarcomas.[15]

Pediatric Considerations

External ring fixation remains the treatment of choice of bone loss in children as bone defects in this age group respond well to grafting, as frames are well tolerated, and as the growth plate may be damaged by a nail. However, recent studies have demonstrated that the circular lesion induced by a nail crossing the distal femoral growth plate is well tolerated in children of 10 years and above.[16] Most internal bone transports reported in this age group have been applied to segmental defects after tumor resections in adolescents.

SURGICAL PLANNING

Preoperative planning is essential to normalize length and alignment—and to order correctly sized implants. Calibrated biplanar radiographs of the affected segment and the contralateral

From the *Rigshospitalet, Copenhagen, Denmark; and †Rubin Institute for Advanced Orthopedics, Baltimore, MD.

J.E.H. is a consultant for NuVasive. U.K.O. declares that there is nothing to disclose.

For reprint requests, or additional information and guidance on the techniques described in the article, please contact Ulrik Kähler Olesen, MD, at ulrik.kaehler@gmail.com or by mail at the Rigshospitalet, Copenhagen 2100, Denmark. You may inquire whether the author(s) will agree to phone conferences and/or visits regarding these techniques.

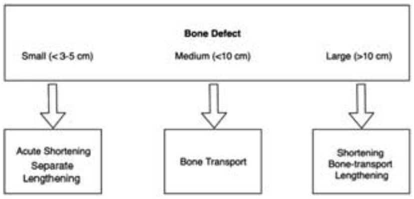

FIGURE 1. Our suggested algorithm.

segment are necessary to determine length, defect size, osteotomy level, canal diameter, and required size of all implants (Fig. 2, 3). Long-standing radiographs of both legs should be obtained whenever possible. Bone transport nails and lengthening nails are currently available from 2 manufacturers: The Wittenstein Company (FitBone) and the NuVasive company (Stryde). Implant length ranges from 280 to 500 mm. The nail diameter ranges from 10 to 12.5 mm. The stroke (ie, the lengthening capability) range from 5 to 10 cm. Bone transport nails can currently transport up to 8 cm without a supplementary procedure. Certain models (the

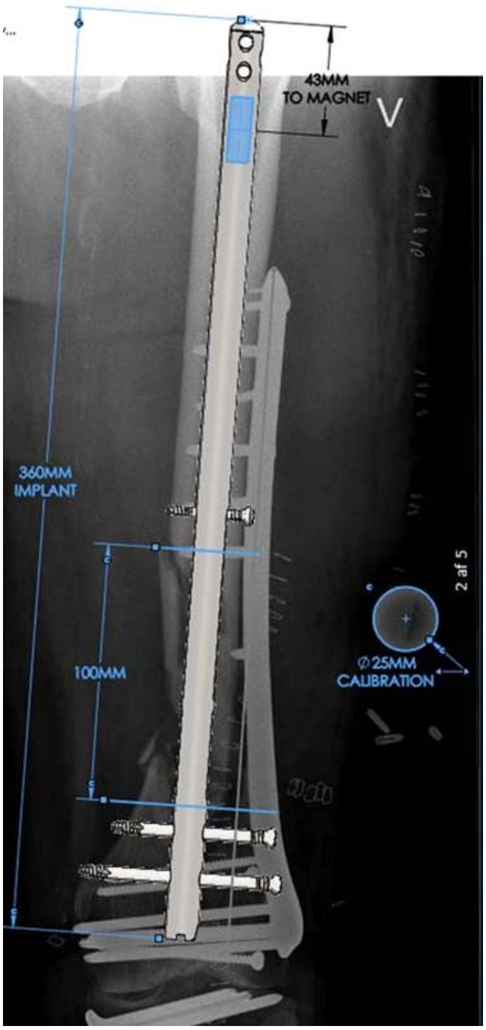

FIGURE 2. An example of a distal femoral defect spanned with a temporary LISS plate with planning of an Transport nail provided by the manufacturer (NuVasive, San Diego, CA). A calibration sphere is included.

FIGURE 3. A 10.5 cm femoral defect, with a concomitant condylar fracture, handled with ~7 cm of transport with a lengthening nail and a plate (PABST) and a supplementary lengthening of 3.5 cm at a later stage, through a secondary osteotomy.

Fitbone FSA/TSA) can convert from transport to lengthening without further intervention (Fig. 4). Certain models allow nearly full weight-bearing (Stryde nails with diameters of 11.5 and up).

We advise sketching the full surgical scenario manually with appropriate scaling of bone segments, bone defect, level of osteotomy, and all implants, ensuring that all steps are clarified, including directionality of the nail and any predistraction that may be needed. TraumaCAD (Brainlab, Munich, Germany) and the BoneNinja iPad application (Rubin Institute for Advanced Orthopedics, Baltimore, MD) are both useful modalities. Technical back-up from the manufacturers with scaled drawings on calibrated radiographs and suggested implants are available on request. Plan for equal limb length and normal alignment of the hip, knee, and ankle joints. Keep in mind that lengthening 1 cm along the anatomic axis of the femur will induce a medial translation of 1 mm of the knee, that should be considered in the planning. The "Reverse Planning Method" by Baumgart[17] is useful to analyze this aspect.

Strategy for Bone Transport

Defects up to 3-5 cm in an adult bone can often be treated with simple shortening and then lengthening through a corticotomy in a nondamaged portion of the bone (Fig. 5, top).

Bone defects of 5 to 10 cm can be treated by a simple 1:1 transport (Fig. 5, middle). In defects > 10 cm, the risk of regenerate insufficiency, soft tissue adhesions, joint contractures, and prohibitively long treatment times, makes serial shortening, transport and then staged lengthening a reasonable option. For example, a defect of 17 cm may be treated by 7 cm of shortening, 10 cm of transport and 7 cm of (secondary) lengthening—preferably in a separate level (bifocal technique) if segment size permits (Fig. 5, bottom). The bifocal technique divides the load on the soft tissues in 2 and minimizes the stress on the bone and the regenerate.

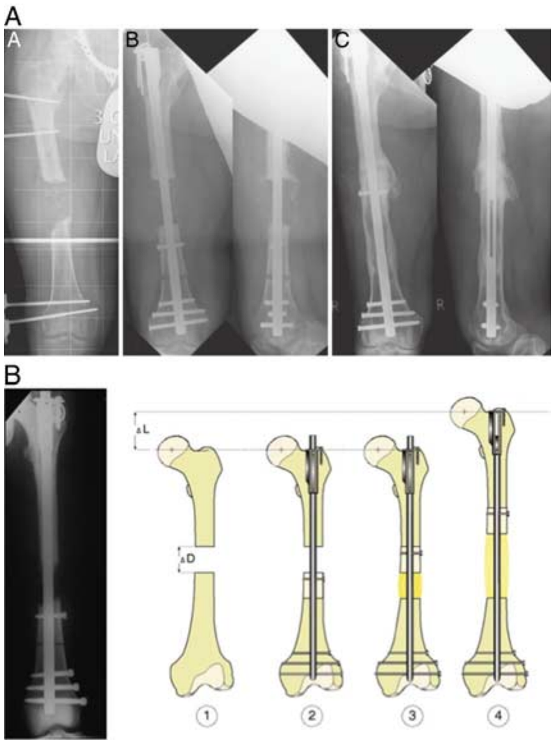

FIGURE 4. A and B, Schematic drawing and x-ray of a femoral bone defect treated with partial acute shortening, bone transport, and then supplementary lengthening starting from the same osteotomy using a Fitbone FSA/TSA nail. Courtesy of Prof. Rainer Baumgart, ZEM, München.

A pause of 6 to 18 months between transport and lengthening in large defects is helpful to restore soft tissue function and range of motion. Occasionally the contralateral segment can be shortened as an alternative to lengthening. Also, unequal knee height (up to 4 cm) is acceptable, so lengthening the segment above or below the injured, when the bone or soft tissue conditions (eg, canal obliteration, unstable skin) makes additional surgical treatment unattractive.

We seek to keep the transport segment at least 6 cm long to maximize stability.

The use of 2 nails (eg, 1 antegrade and 1 retrograde in the femur over a plate) with simultaneous bifocal lengthening has been described, but not published.

Acute Shortening and Fixator Assisted Soft Tissue Closure

Shortening is indicated for smaller defects, bilateral injuries, and in the noncompliant or multitraumatized patient, to reduce complexity and restore other functions before normalizing limb length. A segmental concomitant soft tissue loss may also be an indication for shortening, sparing the patient the use of a free flap and its inherent drawbacks (eg, flap failure, cosmesis, donor site morbidity). This shortening may be combined with rotation and angulation to close soft tissue gaps, a concept known as "fixator assisted closure," slowly distracting soft tissues back to normal alignment before bone transport.[18,19]

Temporary Nailing or Plating

In cases of severe comorbidity, treatment of concomitant injuries, in which external fixation is inconvenient, a temporary nail or plate, spanning the defect is inserted. Not only for the convenience of the patient and nursing staff but also to maintain exact limb length and axis, allow soft tissues healing and preventing contamination from external fixation pin holes—particularly when the time to final surgery is long.

Patient Preparation

Patients should be non-smoking, well-nourished and comorbidities such as diabetes should be optimized to maximize healing and to minimize infection risk. When possible, patients should pretrain the limb. We routinely prescribe calcium and vitamin D.

The final choice of modality, with respect for alternative treatments such as revision arthroplasty and amputation, should be made after a comprehensive and repeated discussion with the patient and his relatives. Patients should also be informed that regaining full range of motion in adjacent joints and pain-free mobility might take 1 to 2 years to achieve (Box 1).

Box 1. Tips and Tricks—Avoiding Pitfalls

- A healthy soft tissue envelope, infection control and meticulous surgical planning with appropriate calibrated imaging is essential. Consult with your plastic surgeons as needed.
- Use life-size calibrated radiographs to simulate the full surgical scenario and all steps included and use computer programs such as TraumaCAD or the Bone Ninja app to assist in planning.
- Tibial defects should be treated with particular precaution, especially the distal tibia.
- Blocking screws are encouraged to avoid inducing deformity and to stabilize the setup, including the regenerate, in particular to prevent femoral varus and tibial antecurvature.
- Small defects can be shortened over a plate and lengthened through a separate osteotomi.
- Replace medium sized defects 1:1.
- Divide treatment of large and complex injuries in 2 (or more) portions, using shortening, transport and lengthening in combination, considering bifocal techniques
- Refer large and complex injuries to dedicated centers.
- Use a dedicated transport nail for diaphyseal defects.
- Use a solid plate to enhance the construct with defects near joints where stability is a concern, in very long defects, and in injuries with concomitant intraarticular fractures (PABST).
- Maintain exact length and axis whenever possible with temporary external fixation, internal nailing or plating, until final surgery.

SURGICAL TECHNIQUE

Internal bone transport is generally performed in 1 of 2 ways: either with a dedicated bone transport nail or with the PABST technique,[10] in which a plate spanning the defect is inserted, followed by an internal lengthening nail, pulling or pushing the segment into place, while the plate stabilizes the construct and aligns concomitant periarticular fractures. However, for simple diaphyseal and metaphyseal defects, without concomitant fractures, a designated bone transport nail is preferred.

At Surgery

A radiolucent grid or an alignment rod is used to check proper alignment and length. The bone ends are squared to bleeding surfaces, to maximize later bone-contact.

Biopsies are taken, whenever infection risk is elevated in open fractures. In cases of malignancy, resection ends must be free of disease. Antirotation markers such as Schanz screws should be used in the femur to monitor and prevent rotational malalignment.

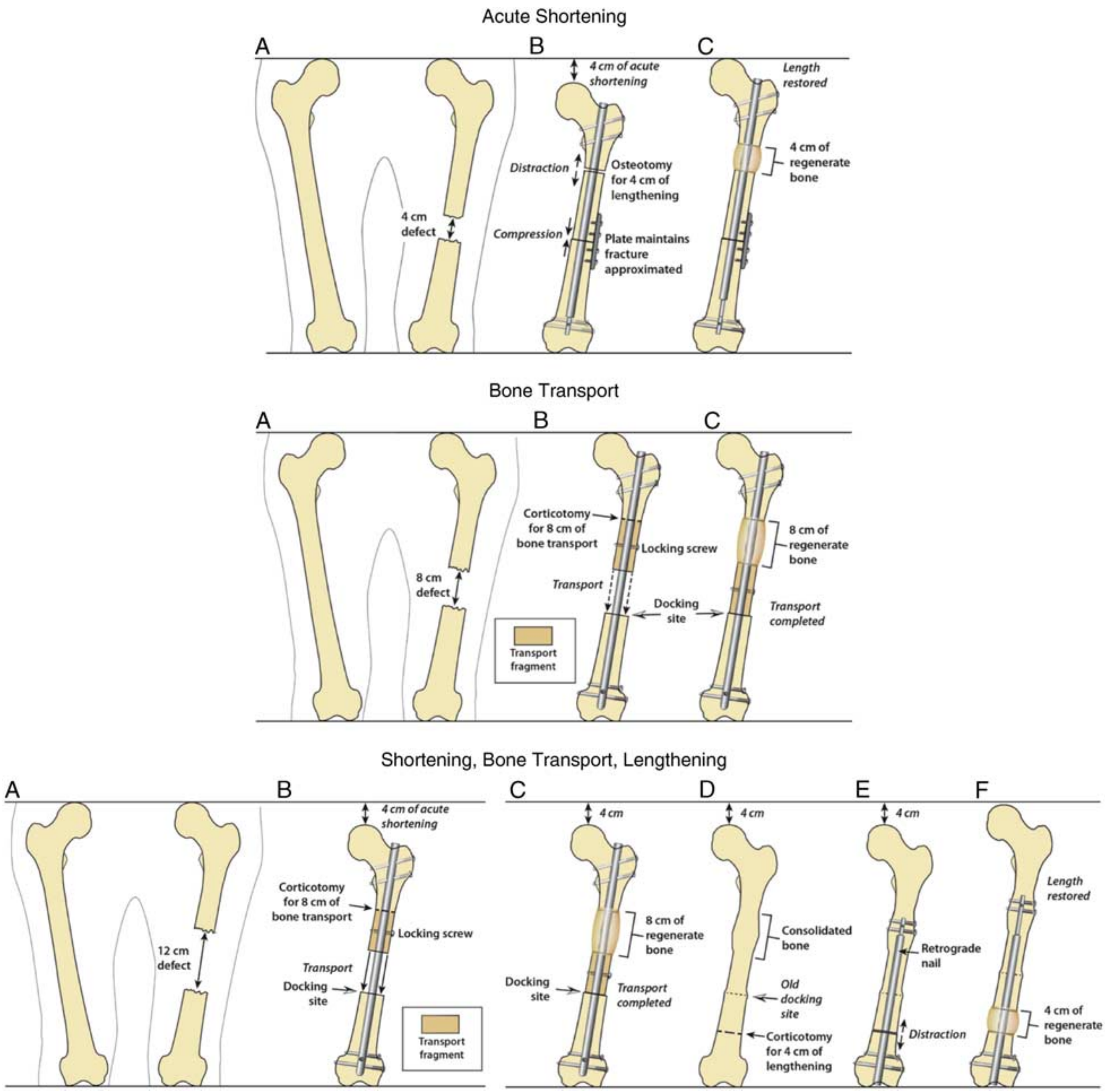

FIGURE 5. Top row: (A–C) Shortening and internal lengthening nail. A, Post traumatic 4 cm defect in the left femur. B, Acute shortening of 4 cm and fixation with a standard lengthening nail. The fracture is kept approximated with a locking plate and unicortical screws. Simultaneously, the femur is lengthened through a corticotomy proximal to the zone of injury. C. After 4 cm of lengthening. The locking plate prevents distraction of the original fracture site. Middle row: (A–C) Transport 1:1 with standard Bone Transport Nail. A, Post traumatic 8 cm defect in the left femur. B, Maintenance of length with a bone transport nail. The fracture is kept approximated with a locking plate and unicortical screws. A corticotomy for transport has been made proximal to the zone of injury. The diaphyseal locking screw transfixes the *napkin ring* bone transport segment (dark bone) to the internal transport mechanism inside the nail, through a slot built into the nail. C, After 8 cm of transport. The transport nail maintains compression at the docking site, so there is no need to add a locking plate here. Bottom row: (A–F) Shortening, transport and secondary lengthening. A, Posttraumatic 12 cm defect in the left femur. B, Acute partial shortening of 4 cm to decrease the required transport length until docking. Fixation with a bone transport nail. The fracture is kept approximated with a locking plate and unicortical screws. A corticotomy for transport has been made proximal to the zone of injury. The diaphyseal locking screw transfixes the napkin ring bone transport segment (dark bone) to the internal transport mechanism inside the nail, through a slot built into the nail. C, After 8 cm of transport. The transport nail maintains compression at the docking site, so there is no need to add a locking plate here. D, After healing of the regenerate bone and the union at the docking site, all hardware is removed. E, As a secondary procedure, a retrograde lengthening nail is inserted and a corticotomy done through virgin bone in the distal metaphysis, distal to the original docking site. F, After 4 cm of lengthening, the original length of the femur has been restored. Copyright Rubin Institute for Advanced Orthopedics, Sinai Hospital of Baltimore, Baltimore, Maryland. All permission requests for this image should be made to the copyright holder.

Reaming

The medullary canal is reamed by 0.5 mm increments at a low speed using flexible reamers up to 1.5 to 2 mm above the diameter of the implant. If using rigid reamers, less over-reaming is required. During reaming, it is essential to consider that the bone transport nails, unlike trauma nails, are straight devices inserted in a curved segment, thus over reaming runs the risk of thinning the cortex excessively.

Osteotomy

The osteotomy is performed percutaneously, sparing the periosteum, using a fresh, sharp drill bit, and finalized with an osteotome. The nail is inserted, spanning the defect, keeping the transport segment in place. Local antibiotics are inserted in the medullary canal at this point[12] if indicated. The nail is locked in both ends, and the transport segment is fixed to the actuator screw in the nail (Fig. 5, middle and bottom).

Plates

If using the PABST technique (Fig. 3), we recommend the use of a solid large fragment plate generally placed on the lateral side, but occasionally a medial plate is used, if the conditions of the soft tissues are in favor of it. The plate should span the entire segment in the tibia and have room for a minimum of 4 screws above and below the defect and the transport segment. The plate is fixed with unicortical screws above and below the transport segment, to leave room for the nail. In the proximal metaphyseal region of the femur and the tibia, the screws should be bicortical—passing through either the designated locking holes in the nail if possible or behind it—to reinforce the construct.

Antegrade or Retrograde, Predistraction of Nail

The location of the defect normally dictates the insertion of the nail in the femur. Tibial nails may be predistracted to fetch a distal transport segment in proximal defects. In the femur, a retrograde (knee) approach may be indicated to treat a diaphyseal defect when hip access is blocked by fracture or arthroplasty, or when a condylar fracture is present (Fig. 6). Generally, the trochanteric entry point is used, sparing the knee.

Docking

Once the transport segment approaches the docking site, soft tissue invagination must be prevented and occasionally a surgical release is required to elevate the invagination and prevent necrosis. The docking procedure is typically initiated when the bony ends are 5 to 10 mm apart, with the removal of fibrous tissue in the gap down to bleeding bone. The bone graft is inserted in the gap and soft tissues are closed—this can also be done percutaneously using a sharp drill bit. The transport procedure is continued until the closure of the bone gap. Continuous pressure at 0.33 mm twice a week for 3 to 5 weeks is applied to stimulate healing. When callus around the docking site is abundant, typically due to hypertrophic ossification in the femur, simple closed compression may be sufficient to induce healing.

Blocking Screws

Maintain normal anatomy during insertion of the nail, by narrowing the medullary canal with blocking screws, particular in proximal tibial defects, where 1 to 2 screws in each plane ensures a centralized placed nail, preventing loss of tibial slope and antecurvature. In the distal femur, similar placements of screws are advised to prevent valgus or varus and to ensure that the transported segment is docking in the center of the condyles.[20] Blocking screws will also enhance the overall stability of the construct.

Additional Length or Transport: Rewinding the Nail

Upon completion of transport, extra length or more transport (when defect size goes beyond the stroke of the nail) may be needed. At this point, calibrated long-standing radiographs of both legs or a full-length radiograph of the contralateral bone are useful to determine the exact length (Fig. 6). In completed bone transport with a simple bone transport nail, the nail is replaced with a lengthening nail. Under the PABST concept, the nail is rewound (actually reshortened or relengthened, depending on what direction the transport is going). The regenerate must be spanned with an external fixator while recharging the device to prevent regenerate collapse, while the nail is not in place or not connected to the bone. The (immature) callus regenerates physiological properties will make it act like a spring and collapse, if not prevented. Specific guidelines and devices such as the "rapid distractor" (NuVasive) and "reverse polarity" technique (FitBone) are available for such procedures.[21]

Exchange Nailing and Hardware Removal

Bone transport and internal lengthening nails should be removed after full, circumferential healing, as they contain technology not intended to remain in the body and as they represent foreign bodies in a potentially contaminated area (eg, open fractures).

Upon completion of transport, the transport or lengthening nail may be removed and replaced by a standard trauma nail. Alternatively, the nail is maintained until full consolidation of the regenerate and full healing of the docking site. Whenever the nail replacement is initiated at docking, while the regenerate is still immature, the insertion of a trauma nail may add in restoring the natural antecurvature of the femur and allow full weight-bearing. Soft tissue contractures that need release can sometimes be addressed at the same procedure (Fig. 6).

Complications

Typical complications in bone transport include heterotopic ossification in the musculature, generating stiffness, in particular in the femur and contractures in the knee and ankle joint. Regenerate insufficiency and delayed maturation, may be countered by bone grafting or injection of bone marrow aspirate concentrate (BMAC).[22] Loosened hardware, must be handled and exchanged promptly, to prevent the collapse of the construct—some surgeons prefer a small plate on top of, for example, an unstable screw and to add additional blocking screws. Implant failure, bending, and breakage are rare, but occur, and must lead to hardware exchange.[23]

Deep bone infection is treated with removal or replacement of implants, debridement, and irrigation, local and systemic antibiotics, or even conversion to external ring fixation.

Delayed union of the docking site may require additional bone grafting and a short course of distraction and compression to stimulate healing. Neurovascular injuries to the peroneal nerve and compartment syndromes in the tibia may occur and require surgical release and decompression.

Contracture

Occasionally closed contracture release—or open surgery is needed to release muscular adhesions, but only after intensive physiotherapy, without improvement over months—sometimes in conjunction with hardware exchange. Typically, a quadriceps release between the vastus intermedius and the rectus is performed.

Many patients, in particular after open tibial fractures, will inevitably have a degree of lifelong residual fibrosis, edema, and paresthesias, despite successful bone replacement.

FIGURE 6. Long standing radiographs upon completed reconstruction of a bilateral open femoral fracture with bone loss. The right side was acutely shortened then lengthened, the left side was treated with pabst technique. Final x-rays show equal limb length and normal axis.

POSTOPERATIVE PROTOCOL

Bone Transport

Initiate transport after a 5 to 7 days latency, at a rate and rhythm of 0.33 mm thrice daily in the femur and 0.25 mm thrice daily in the tibia. Slower rates may be indicated in patients with fragile soft tissues, smokers, and diabetics. Radiographs should be made every 2 weeks, and based on the robustness or lack thereof in the regenerate bone, rates should be adjusted up or down. If marked restrictions in joint range of motion occur, the treatment should be paused.

Weight-bearing

Weight-bearing is allowed depending on the specific tolerance of the implants with respect to their diameter and patient weight. In cases of PABST, full weight-bearing is usually not allowed until docking. We like to see at least one full cortex of regenerate bone before discontinuing crutches.

Physiotherapy

Vigorous physiotherapy throughout the course of treatment is encouraged to minimize loss of muscle function contracture tendency, in particular, equinus in the ankle joint and flexion contracture in the knee joint.

REFERENCES

1. Baumgart R, Betz A, Schweiberer L. A fully implantable motorized intramedullary nail for limb lengthening and bone transport. *Clin Orthop Relat Res*. 1997;343:135–143.
2. Rozbruch SR, Birch JG, Dahl MT, et al. Motorized intramedullary nail for management of limb-length discrepancy and deformity. *J Am Acad Orthop Surg*. 2014;7:403–409.
3. Dahl MT. Motorized, telescopic, intramedullary lengthening nails for limb length and deformity correction. *Techniques in Orthopaedics*. 2015;30:189–206.
4. Papakostidis C, Bhandari M, Giannoudis PV. Distraction osteogenesis in the treatment of long bone defects of the lower limbs: effectiveness, complications and clinical results; a systematic review and meta-analysis. *Bone Joint J*. 2013;95-B:1673–1680.
5. Horn J, Grimsrud Ø, Steen H, et al. Femoral lengthening with a motorized intramedullary nail. A matched-pair comparison with external ring fixator lengthening in 30 cases. *Acta Orthop*. 2015;86:248–256.
6. Landge V, Shabtai L, Herzenberg JE, et al. Patient satisfaction after limb lengthening with internal and external devices. *J Surg Orthop Adv*. 2015;24:174–179.
7. Kähler Olesen U, Singh UM, McNally M, et al. The cost of infection in severe open tibial fractures treated with a free flap. *Int Orthop*. 2017; 41:1049–1055.
8. Holm I, Steen H, Bjerkreim I. Muscle function after mid-shaft femoral shortening. A prospective study with a two-year follow-up. *Bone Joint Surg Br*. 1994;76:143–146.
9. Barker KL, Simpson AH. Recovery of function after closed femoral shortening. *J Bone Joint Surg Br*. 2004;86:1182–1186.
10. Kähler Olesen U, Prince D, Nygaard T, et al. Plate-assisted bone segment transport with motorized lengthening nails and locking plates: a technique to treat femoral and tibial bone defects. *J Am Acad Orthop Surg Glob Res Rev*. 2019;3:e064.
11. Kähler Olesen U, Juul R, Bonde CT, et al. A review of forty five open tibial fractures covered with free flaps. Analysis of complications, microbiology and prognostic factors. *Int Orthop*. 2015;39:1159–1166.
12. Morgenstern M, Vallejo A, McNally MA, et al. The effect of local antibiotic prophylaxis when treating open limb fractures: a systematic review and meta-analysis. *Bone Joint Res*. 2018;7:447–456.
13. Jacobs N, Sutherland M, McNally M, et al. Distraction osteogenesis for reconstruction of primary malignant tumour of long bones. *Bone Joint J*. 2014;96-B(supp 10):28.
14. Lesensky J, Prince D. Distraction osteogenesis reconstruction of large segmental bone defects after primary tumor resection: pitfalls and benefits. *Eur J Orthop Surg Traumatol*. 2017;27:715–727.
15. Baumgart R, Hinterwimmer S, Krammer M, et al. The bioexpandable prosthesis: a new perspective after resection of malignant bone tumors in children. *J Pediatr Hematol Oncol*. 2005;27:452–455.
16. Shabtai L, Specht SC, Standard SC, et al. Internal lengthening device for congenital femoral deficiency and fibular hemimelia. *Clin Orthop Relat Res*. 2014;472:3860–3868.
17. Baumgart R. The reverse planning method for lengthening of the lower limb using a straight intramedullary nail with or without deformity correction. A new method. *Oper Orthop Traumatol*. 2009;21:221–233.
18. Ullmann Y, Fodor L, Lerner A, et al. The revised “reconstructive ladder” and its applications for high-energy injuries to the extremities. *Ann Plast Surg*. 2006;56:401–405.
19. Beltran MJ, Ochoa LM, Hsu JR, et al. Composite bone and soft tissue loss treated with distraction histiogenesis. *J Surg Orthop Adv*. 2010;19:23–28.
20. Muthusamy S, Rozbruch SR, Fragomen AT. The use of blocking screws with internal lengthening nail and reverse rule of thumb for blocking screws in limb lengthening and deformity correction surgery. *Strategies Trauma Limb Reconstr*. 2016;11:199–205.
21. Schiedel F. Extracorporal noninvasive acute retraction of STRYDE® for continued lengthening in cases with limited nail stroke: a technical less invasive solution to reload the STRYDE®. *Arch Orthop Trauma Surg*. 2020. [Epub ahead of print].
22. Gessmann J, Köller M, Seybold TA. Regenerate augmentation with bone marrow concentrate after traumatic bone loss. *Orthop Rev (Pavia)*. 2012;4:e14.
23. Morrison TA, Sontich J. Premature consolidation with resultant implant failure using PRECICE femoral nail lengthening: a case report. *J Bone Jt Surg*. 2016;6:e2.