Expert Review of Medical Devices

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/ierd20

Technical considerations for the management of segmental osseous defects with an internal bone transport nail

Lee M Zuckerman, John A Scolaro, Matthew P Gardner, Thomas Kern, Philipp Lanz, Stephen M. Quinnan, J. Tracy Watson & Jan Duedal Rölfing

EXPERT REVIEW OF MEDICAL DEVICES
https://doi.org/10.1080/17434440.2022.2054336

Taylor & Francis
Taylor & Francis Group

DEVICE PROFILE

Technical considerations for the management of segmental osseous defects with an internal bone transport nail

Lee M Zuckerman [a], John A Scolaro [b], Matthew P Gardner [c], Thomas Kern [d], Philipp Lanz [e], Stephen M. Quinnan [f], J. Tracy Watson [g] and Jan Duedal Rölfing [h]

[a]Division of Orthopaedic Surgery, City of Hope National Medical Center, Duarte, CA, USA; [b]Department of Orthopaedic Surgery, University of California Irvine School of Medicine, Irvine, CA, USA; [c]Department of Orthopaedic Surgery, Southern Illinois University School of Medicine, Springfield, IL, USA; [d]Department of Orthopaedic Surgery, BG Hospital Murnau, Murnau am Staffelsee, Germany; [e]Departments of Orthopaedic Surgery, Medical University of Graz, Graz, Austria; [f]The Paley Orthopedic and Spine Institute, St. Mary's Medical Center, West Palm Beach, FL, USA; [g]Department of Orthopaedic Surgery, Saint Louis University School of Medicine, St. Louis, MO, USA; [h]Orthopaedic Reconstruction, Aarhus University, Aarhus, Denmark

ABSTRACT

Introduction: Traditionally, distraction osteogenesis has been accomplished with an external fixator. All internal transport utilizing magnetic intramedullary nails is a newer technique for bone reconstruction. The Precice Bone Transport Nail is a new implant that allows for noninvasive transport via a magnetically driven motor.

Areas covered: This report describes the function of the Bone Transport Nail along with the technical considerations on how to successfully manage bone defects with this new technology. Appropriate use of the nail, preoperative planning, intraoperative considerations, and postoperative management are discussed in detail.

Expert opinion: The Precice Bone Transport Nail utilizes the technology of the original Precice nail to provide an all-internal option for reconstruction of intercalary defects. This obviates the need for an additional plate with a standard Precice nail when performing bone transport and allows for a less invasive option that decreases operating room time. It provides a more cosmetic result than external fixation and avoids the risks of pin tract infection. Preoperative planning is essential to appropriate execution of the operative procedure and to perform a successful transport. A thorough understanding of the nail design and limitations are a prerequisite as this implant is significantly different from a standard intramedullary nail.

ARTICLE HISTORY
Received 5 January 2022
Accepted 10 March 2022

KEYWORDS
Bone loss; distraction osteogenesis; intercalary defect; limb-salvage; metastatic disease; nonunion; Precice bone transport nail; sarcoma

1. Introduction

Distraction osteogenesis with bone transport provides a biologic reconstruction with a well vascularized bone segment which has biologic and clinical advantages over traditional reconstructive techniques [1–4]. The transport segment is able to hypertrophy and respond to functional loading in a rapid manner not seen with traditional grafting techniques. Bone transport has traditionally been accomplished with an external fixator. Some techniques have used ring fixators or monolateral frames for bone transport over a nail (BTON), external fixator assisted balanced cable transport, and external fixator transport followed by immediate nailing and frame removal (TATN – transport and then nail) [1,5–8].

External fixators have the inherent risk of pin tract cellulitis or infections, joint contractures or subluxations, risk of nonunion at both the docking and regenerated sites due to premature frame removal, and refracture at the docking site [9–14]. Prolonged time in the external fixator can cause detrimental psychological effects for the patient and soft tissue scarring can result in poor cosmesis [15,16].

Techniques of intercalary defect management using a totally implantable device have been previously described using the Precice lengthening nail (NuVasive Specialized Orthopedics, Inc., Aliso Viejo, CA). Bone transport with distraction osteogenesis using a Precice nail has been achieved by transporting a segment of bone with the Precice lengthening nail while stabilizing the docking site and regenerate with a spanning plate (plate-assisted bone segment transport – PABST) [17–21]. Another technique for reconstructing critical sized bone defects with a Precice nail without distraction osteogenesis uses a predistracted Precice nail to compress intercalary allograft [22]. The advent of the Precice Bone Transport Nail (BTN) (NuVasive Specialized Orthopedics, Inc., Aliso Viejo, CA) now provides an implantable all-internal option for management of critical bone loss via distraction osteogenesis without the need for external fixation or supplemental plate fixation. This new implant requires distinct preoperative planning, surgical execution and postoperative management when compared to the standard Precice nail.

CONTACT Lee M Zuckerman lzuckerman@coh.org City of Hope National Medical Center, Division of Orthopaedic Surgery, 1500 E. Duarte Rd, Duarte, CA 91010, USA

Article highlights

- Pre-operative planning is essential to choose the correct nail length, establish whether a screw exchange or pit stop is required, and to plan the location of the corticotomy to maximize transport.
- The corticotomy should be made carefully as comminution or propagation of a fracture may compromise screw fixation.
- Blocking screws should be planned and placed as needed to aid in proper nail placement and prevent iatrogenic deformity.
- Cables can be used to assist in transport of the intercalary segment when screws are not able to be placed.
- The weight limits of the nail should be strictly followed to prevent catastrophic failure of the nail.
- Regularly scheduled radiographs are necessary during transport to ensure adequate regenerate formation, decrease the risk of early consolidation, and to adjust the transport rate if necessary.

2. Design considerations

In some respects, such as having proximal and distal locking screws, the Precice BTN resembles a standard interlocked intramedullary nail. However, the BTN contains a smaller diameter rod internally that moves within the center of the larger, outer slotted rod. The inner rod has holes in two positions for screws that are used to link the rod to the transport segment. A magnetically driven motor is contained within the nail which drives only the inner rod. An external remote controller (ERC) or fast distractor can be used to move the inner rod in an antegrade or retrograde manner. The ERC is used by the patient and moves the screws at a rate of 1 mm per 3–7 minutes depending on the ERC model. The fast distractor can be used intraoperatively to position the holes for the screws at a rate of 7 mm per minute. One or two transport slots exist within the nail, and the size, number and location of the transport slots depends on the nail length. The BTN is currently indicated to perform up to 10 cm of bone transport, but transport lengths greater than 7 cm will require a screw exchange across the bridge from one slot to the next. The various nail lengths have their own limits of bone transport which is necessary to take into account when templating. If two windows are available, a screw exchange may be necessary to transition the screws to the adjacent window. When there is enough bone proximal to the original placement of the intercalary screw, a 'pit stop' and 'recharge' can be performed to reset the location of the screws within the transport segment. If a recharge can be performed then the segment can be transported beyond the maximum distance allowed in the window.

3. Pre-operative considerations

Pre-operative planning is paramount to the successful treatment with the BTN and notably more so than with most other reconstructive procedures given the technical considerations around the nail that is chosen. Similar to other techniques that require patients to be regularly involved with their implants, thoroughly understanding the treatment and necessary compliance is critical to success.

If bone transport is being planned for bone loss after tumor resection, confirming negative margins by intraoperative frozen section or temporarily stabilizing the bone until the final pathology is returned decreases the risk of local recurrence and contamination. In cases of open fractures, infected nonunions, or resection of osteomyelitis, the first step is to debride all contaminated, infected and nonviable tissue. The next critical component of early treatment is to obtain adequate soft tissue coverage. The initial debridement should include removal of any peripheral bony pieces in the area where transport will occur to produce a well circumscribed and unobstructed transport trajectory. Temporary fixation with an antibiotic spacer such as an antibiotic coated nail or plate can be used as an adjunct to stage reconstruction when infection is present (Figure 1(a,b)). The antibiotic spacer is made with PMMA as this will create a 'tube' and condition the surrounding tissues for later transport thru this soft tissue conduit and thereby minimize soft tissue invagination at the docking site. This technique of transporting a bone segment through an induced membrane has been described previously [23,24]. Measurements of the anticipated defect should be performed intraoperatively, even if transport is staged, in order to supplement templating before the staged procedure.

3.1. Templating

Pre-operative templating is necessary in order to determine the correct nail length, stroke length available, location of the corticotomy, location of the intercalary screws, and whether a screw exchange or pit stop and recharge of the nail is required (Figure 1(c)). Calibrated radiographs are essential in order to template properly. If implants are in place and the sizes are known, these can be used to confirm that the radiographs are calibrated properly. Full length, long leg alignment films such as bilateral scanograms should also be obtained to evaluate for any mechanical axis deviation, limb segment deformities, or any leg-length discrepancy. Once appropriate calibrated radiographs are available, templating of the case should be performed and the first thing that must be determined is the length of the longest possible BTN that can be placed within the bone. The next question, which may be known from prior intraoperative measurements, is how much transport or stroke length is needed from the nail. These two pieces of information taken together will guide the choice of what length nails could be used to achieve the desired transport. Once the nail length options are known, it is necessary to template where the nail will sit within the bone to make certain that an osteotomy is feasible in the zone allowed by the chosen nail. This is especially relevant in the proximal tibia where the osteotomy should not go through the tibial tuberosity but is also relevant to anatomical constraints in other locations. Templating will also allow determination of whether the transport can be performed with a single slot within the nail or if a screw exchange or potentially a pit stop and nail recharge is needed. Using a shorter nail with endcaps can also

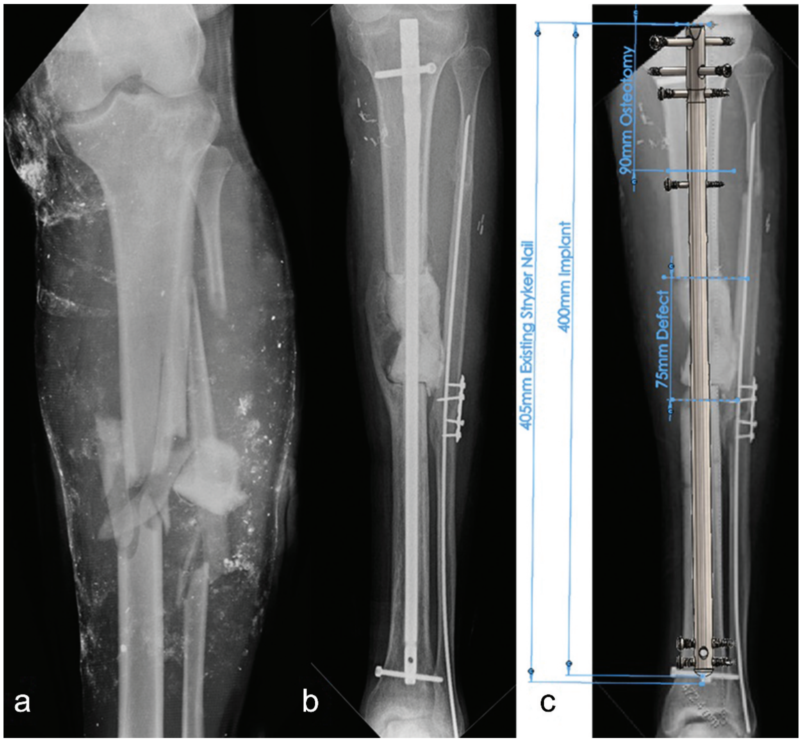

Figure 1. (a) Anterior-posterior (AP) radiograph of a comminuted, open tibial shaft with associated fibular fracture. (b) After thorough debridement, temporary fixation is performed with an intramedullary nail and antibiotic cement. The length of the fibula is restored in order to optimize limb-lengths. (c) In preparation for placement of the Bone Transport Nail, templating determines the length of the implant, site of the osteotomy, and the defect that has to be bridged. The length of the temporary nail is used to confirm measurements.

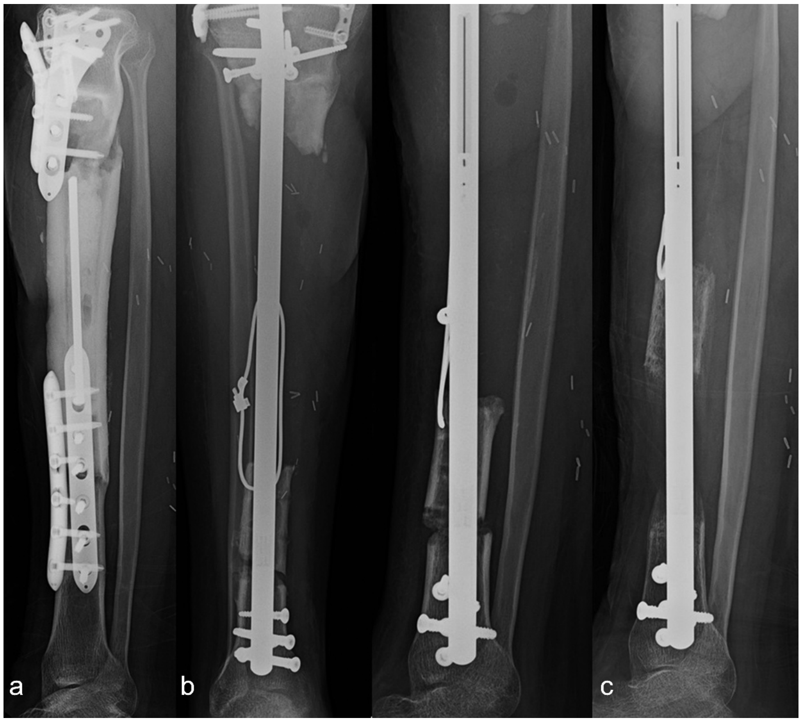

Figure 2. (a) Lateral radiograph of a patient who sustained a fracture through an intercalary allograft after tumor resection. (b) After removal of the allograft, an AP and lateral radiograph demonstrates that the intercalary screw holes are not within range of the transport segment, and therefore cable-assisted transport is performed. (c) After transport in the distal window was completed, the nail was recharged, and the cable was exchanged for continued transport. Once the transport segment is within range, an intercalary screw will be placed.

be templated to adjust the location of the transport windows if necessary. If the transport segment is not within the range of a single slot in the nail, then a cable-assisted transport can be performed initially and then switched to a screw during a subsequent procedure (Figure 2).

3.2. Nail length

The nail length and location of the corticotomy must be planned carefully. The location of the nail should allow for as many proximal and distal interlocking screws as possible to be placed for increased stability (Figure 2) [25]. The proximal threads of the interlocking screws are larger than the interlocking holes and templating will ensure these screws will obtain proper purchase and not impinge on the nail. If the transport will be over a long distance, the corticotomy should be made as close to the adjacent interlocking screws as possible without compromising the screw. Typically, this means leaving at least 3 mm of bone between the locking screw and the osteotomy. The optimal position of the intercalary screw holes and whether a screw exchange or nail recharge can take place or is necessary should be anticipated in order to complete the transport (Figure 3(a,b)). Although two intercalary screws will increase fixation into the transport segment, the use of only the proximal screw is necessary to facilitate a screw exchange across the slot bridge. If the corticotomy is placed too close to the intercalary screws a recharge may not be possible. When necessary, the intercalary screws can be placed through the regenerate for continued transport when the regenerate is mature enough (Figure 3(c)). If the regenerate is healed, a new osteotomy will have to be performed to continue transport. The nail can either be temporarily removed if this is necessary or the osteotomy can be performed around the nail, taking extreme care not to damage the nail.

3.3. Blocking screws

Blocking or stabilization screws should also be templated and used frequently, not just to assist with deformity correction, but to provide added stability and prevent deformities from developing during distraction. Having a tight cortical fit with the nail is necessary to prevent secondary deformity, particularly in shorter metaphyseal segments. The tension produced in the soft tissues increases as transport progresses, and the bone segments are likely to drift into deformity without stabilization screws if there is only minimal cortical contact. This phenomenon is especially evident in the tibia where valgus and apex anterior deformities occur if the nail is undersized and not stabilized in the metaphyseal regions. Stabilization screws are placed adjacent to the nail and provide increased stability by substituting for a bony cortex and thus prevent this problem.

3.4. Intraoperative considerations

During placement of the BTN, limb-length as well as rotational and angular alignment should be optimized. If the tibia is being treated, reestablishing the length of the fibula can help ensure the tibia is out to length (Figure 1(b)). Intra-operative measurements of the contralateral limb can also be used both clinically and with fluoroscopy to ensure equal limb-lengths. Blocking screws, a temporary external fixator, and temporary Schantz pins can all be used to ensure rotational and angular alignment are correct. In the femur, it is important to understand that the

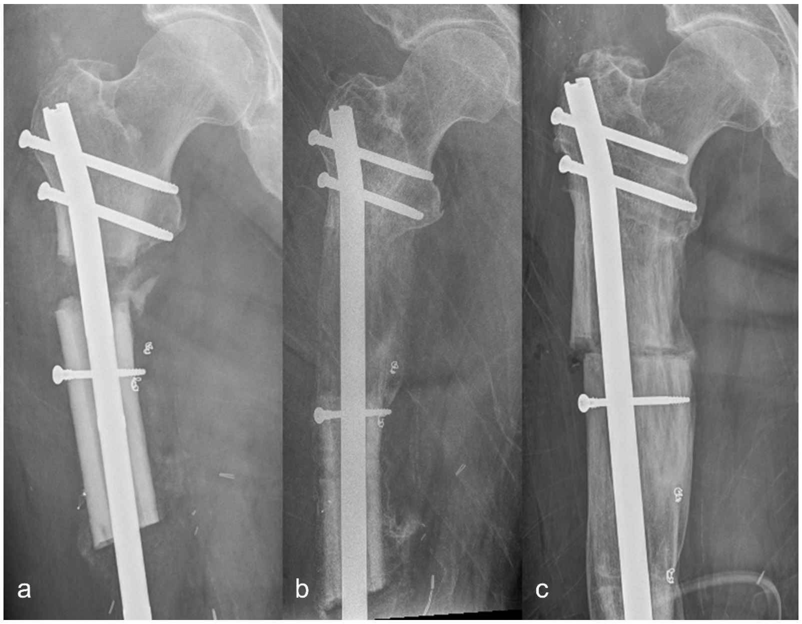

Figure 3. (a) AP radiograph during transport shows that adequate bone remains in the proximal transport segment to perform a recharge. (b) After a screw exchange and completion of transport in the distal window, the nail is recharged to continue transport. (c) Further transport was necessary, and the nail was recharged again with a screw placed through the regenerate. In this case, the regenerate had healed and a new corticotomy was placed through the regenerate. The nail was temporarily removed to perform the corticotomy and new locations for the proximal locking screws were used to maximize purchase.

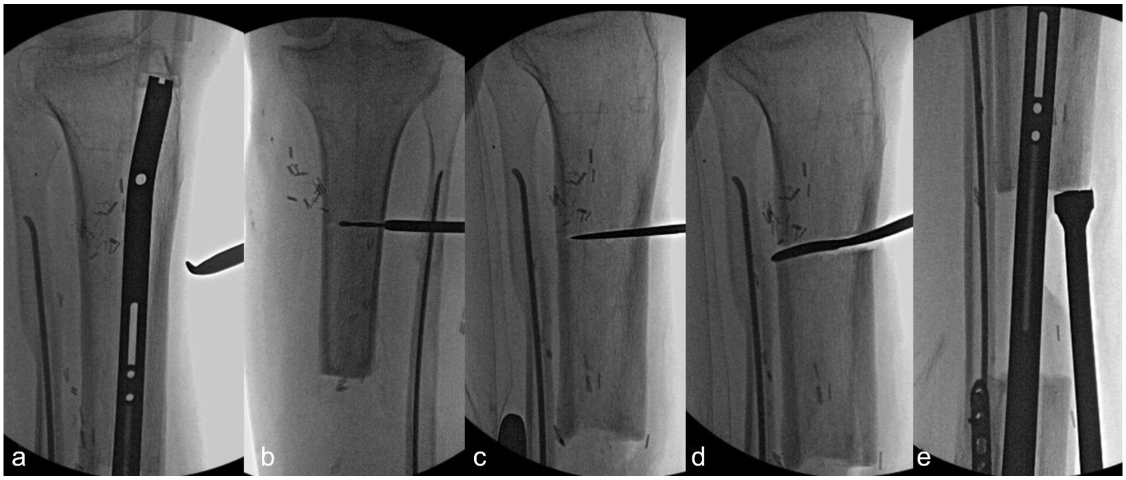

Figure 4. (a) Fluoroscopic images of the lateral tibia show the nail overlying the tibia to determine the location of the osteotomy. (b) The osteotomy is then performed using sharp drill bits and (c) completed with an osteotome. (d) An elevator is then used to confirm completion of the osteotomy. (e) After the nail is placed and prior to placement of the intercalary screws, a bone tamp is used to ensure there is no gapping at the osteotomy site.

nail is straight and therefore iatrogenic procurvatum and recurvatum can occur with improper placement of the nail. If a temporary nail, plate, or antibiotic spacer is in place and the alignment and leg-lengths are accurate, a temporary external fixator can be used to maintain proper alignment.

The integrity of the membrane around the antibiotic spacer should be preserved as this will help maintain a tunnel for the bone to transport and enhance healing at the docking site. The bone ends should be resected back to healthy, bleeding bone and at least 75% of the bone circumference should be intact [26]. Additionally, the bone ends should be flush and as parallel to each other as is possible. This optimizes the biology and mechanics at the docking site when the transport is complete by having large flat bleeding bone surfaces capable of being well apposed and compressed as the regenerate heals.

Placement of the guidewire for reaming should be accurate based on templating. Blocking screws can be placed at this point in order to prevent eccentric reaming or blocking wires can be used during reaming and later replaced with stabilization screws after the nail is in place. The proximal segment should be reamed 2 mm above the nail diameter in order to allow for ease of nail placement and transport of the intercalary segment without binding on the nail. If a short segment is present, correct placement of the guidewire for reaming is essential to maintain limb alignment. The distal segment may be reamed to only the diameter of the nail to increase stability of the construct.

Determining the site of the corticotomy has typically been performed by inserting the BTN, marking the corticotomy with a Steinmann pin, and removing the nail to perform the corticotomy. An alternative is to place the nail over the limb under fluoroscopic control to confirm the site of the corticotomy that was determined during templating and accepting the small amount of magnification error (Figure 4(a)). In addition to this, dummy nails are now available as trials that can be inserted into the bone to confirm the level of the corticotomy and possibly to place stabilization screws without fear of damaging the BTN.

Placing the BTN or a dummy nail has the advantage of ensuring that limb-lengths and deformities have been corrected with the nail in place. It also provides visual confirmation that the bone cuts are parallel, and the nail may be removed if further debridement is necessary. Prior to nail placement, the guidewire has to be removed as the nail is not cannulated, and therefore proper reaming and placement of blocking wires or screws is essential. Once the preparation is satisfactory, the nail should be pulled back proximal to the corticotomy site and a small incision should be made at the site of the corticotomy. Using these nails often demands the osteotomy be in a very specific location due to the limited distance between the top of the transport slot and the locking screws. Thus, fracture propagation of the osteotomy can be a major problem and should be avoided at all costs. Although multiple drill hole osteotomies are most commonly used, some surgeons may prefer a Gigli saw osteotomy in order to minimize the possibility of fracture propagation at the osteotomy site. When performing a multiple drill hole osteotomy, cooling measures and sharp drill bits should be used (Figure 4(b)). Multiple drill bits may be necessary to prevent necrosis of the bone from a dull drill bit. After multiple drill holes are made, a sharp osteotome should complete the osteotomy (Figure 4(c)). Some comminution may occur at the opposite cortex which will not impede regenerate formation but should be avoided if it will affect screw purchase. Completion of the osteotomy can be confirmed with fluoroscopy by mobilizing the transport segment with an elevator or osteotome (Figure 4(d)).

Alternatively, a Schantz pin can also be inserted into the transport segment juxtaposed to the nail just prior to withdrawing the nail and performing the corticotomy. Once the corticotomy is performed, the Schantz pin can be used as a joystick to counter rotate the transport segment and perform a closed osteoclasis to the posterior cortex. The nail can then be inserted, and the joystick used to prevent distal migration and distraction of the transport segment and avoid a post corticotomy diastasis.

Prior to final nail placement if locking screw position adjustment is needed, the fast distractor should be used to move the intercalary locking screws into proper position based on templating. The nail should then be placed across the osteotomy site and into the distal fragment. If the Schantz pin for transport segment stabilization is not used and there is displacement of the transport segment with nail placement, a bone tamp or Kocher clamp can be placed through the open wound, if available, to ensure the transport segment has good osseous contact at the corticotomy site (Figure 4(e)).

As many proximal and distal interlocking screws as possible should be placed in order to obtain maximal stability, particularly if a short segment is present. A step drill is used to place the partially threaded screws and the tactile feedback after penetrating the far cortex can be lacking. In order to prevent poor purchase of the screws, fluoroscopy can be used to determine when the drill bit has been advanced through the second cortex. Additional stabilization screws can also be added, abutting the nail to provide further stability and to prevent migration post-operatively. Drilling for the 3.5 mm intercalary screw can sometimes prove difficult in thick, cortical bone. Drilling a pilot hole with a K-wire or smaller diameter drill bit can be used if necessary. The location of the magnet in the BTN should be marked on the patient and it is helpful to place a nonabsorbable stitch in this location for the patient to reference. The fast distractor or ERC should be used to confirm that the intercalary segment moves by advancing the segment 1 mm (Figure 5). Alternatively, the nail can be predistracted a few millimeters prior to placement to allow the nail to be tested by compressing the osteotomy site and thereby minimize bone gapping during the latency period. The final defect should be measured.

4. Post-operative considerations

Post-operatively, the transport protocol should be based on the location of the nail in addition to the patient's age and co-morbidities. A latency of 7 to 14 days is typical when using external fixation. Duration of latency with the BTN is modified based on the age of the patient, location of osteotomy and patient comorbidities. The femur transport starts at 0.75 mm to 1.0 mm per day divided into three or four sessions. The tibia transport should proceed at 0.5 mm to 0.75 mm per day divided between two to four sessions (e.g. 0.15 mm 4x daily). The patient should be followed regularly with radiographs in order to ensure compliance with the transport and monitor regenerate formation. If there is a lack of regenerate, halting or reversing transport can be considered. If the patient starts developing pain with transport or there is significant regenerate, the transport rate should be increased to prevent premature consolidation that would require a repeat osteotomy. Weight bearing is based on the diameter of the nail in addition to the stability of the construct. Range of motion of the adjacent joints is ideally started as soon as possible.

4.1. Screw exchanges and pit stops

If a screw exchange or pit stop is necessary, the transport segment should never be left uncaptured and should be stabilized by locking screws, a temporary plate, temporary external fixation, or other means. This is necessary because prior to becoming calcified, the regenerate acts as a large collagen spring and will pull on the transport segment causing regenerate rebound. Regenerate rebound results from the inherent tension within the regenerate column that will cause it to spring back and shorten when left uncontrolled. For example, a screw exchange consists of adding an intercalary locking screw to the far hole across the bridge and then removing the near intercalary locking screw. The preexisting near screw should be left in place until the new far locking screw is in place to both stabilize the transport segment for screw placement and to prevent regenerate rebound. Once the new screw is in place, the initial screw can be safely removed. The transport then proceeds in the standard fashion until it is complete. If the transport segment is close to docking but there is no space remaining in the slot, it may be possible to perform a pit stop to recharge the nail. The nail can be recharged, and a new locking screw engaged for as much additional transport length as there is bone available

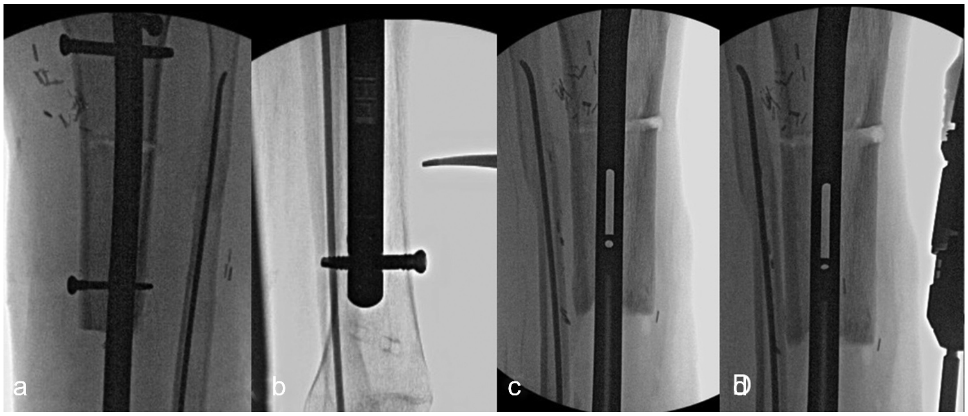

Figure 5. (a) Once the intercalary screw is placed, (b) the magnet is localized. (c) Prior to magnet activation, a lateral fluoroscopic image localizes the intercalary screw and osteotomy site. (d) After magnet activation and 1 mm of transport, movement of the intercalary screw and gapping of the osteotomy site is confirmed.

above the locking screw. Recharging the nail requires removing the existing all locking screws from the transport segment, so it is critical to capture the transport segment. Options for temporary fixation of the transport segment during the recharge process include external fixation, a small locking plate and screws, a clamp locked in a static position, or possibly a syndesmotic screw in the tibia (Figure 6(a)). Once the transport segment is captured, a fast distractor can be used to reposition the transport segment locking holes further back up the nail. The locking screws can then be placed in this new location and the temporary fixation removed. The transport can then proceed as normal until complete [27].

4.2. Docking procedures and completion of transport

Multiple options are available if a docking procedure is planned. Some prefer to prepare the docking site when docking is 1 cm away, while others prefer to complete the transport and then back it up 5 mm with a fast distractor to allow preparation of the docking site and immediate apposition of the docking site with compression. Either way, a second intercalary screw can be placed during this procedure, if it is not present, to increase stability (Figure 6(b)). The authors have seen success with continued compression without a docking procedure especially when heterotopic bone and callous are present, and this can also be considered. However, longer transports or those with less complete bone apposition will likely benefit from a formal docking procedure. If no progression of union is identified, then a delayed docking procedure should be performed such as grafting the docking site. Once transport and docking are complete, continued compression is recommended at a slower rate of 0.25–0.33 mm daily every other day until the patient notes discomfort with transport or the intercalary screw starts to bend (Figure 7).

If the BTN is to be removed, a trauma nail or plate can be placed for added stability while the regenerate and docking sites consolidate. If the intercalary screw is bent, care must be taken during removal to prevent it from breaking. Once the nail is engaged with an extractor, the interlocking screws should be removed. The fast distractor can then be used to reverse the intercalary screw by a millimeter in order to take pressure off the intercalary screw prior to removal. If the regenerate has not consolidated or the docking site has not fully healed, temporary fixation with an external fixator or plate should be considered to prevent loss of alignment and shortening of the limb.

5. Conclusion

The Precice BTN is a novel technology that allows for in-line distraction osteogenesis without external rings, pins, wires or cables. It similarly obliviates the need for supplemental internal plate fixation. The device provides the stability and benefits of an intramedullary implant positioned along the anatomic axis of the limb. In addition, the nail also ensures the transport segment moves directly between its origin and destination. Finally, without external components, the nail allows for bone transport beneath compromised soft tissue envelopes and flaps without any concern for complication. Similar to other techniques utilized for distraction osteogenesis, patient selection and pre-operative planning are critical to the success of this technique.

Figure 6. (a) Prior to removal of the intercalary screw during a docking procedure, a clamp is used to hold the transport segment to prevent migration. (b) With the clamp in place, the intercalary screw is removed, the nail is recharged, and two intercalary screws are placed. (c) Maturation of the regenerate and healing of the docking site is demonstrated.

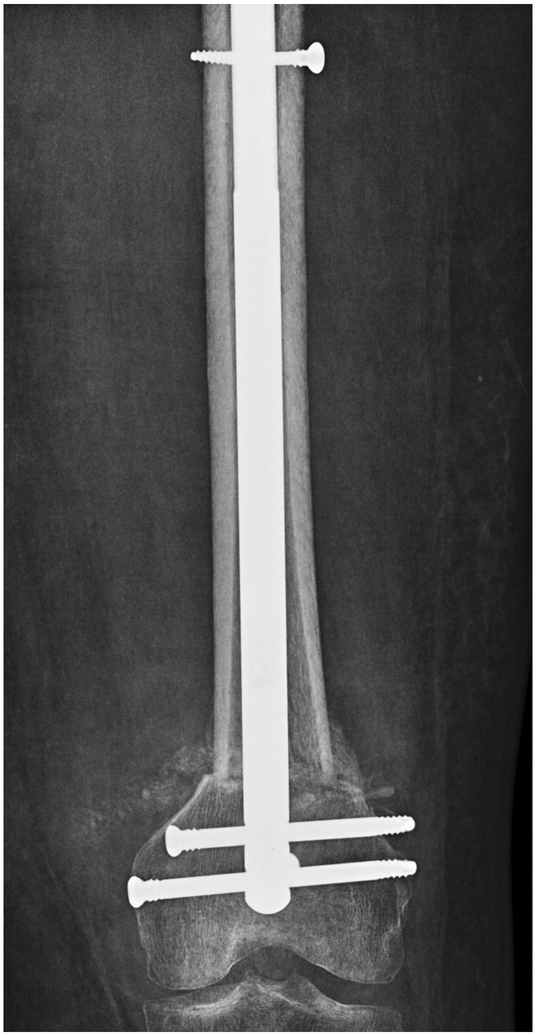

Figure 7. After docking has occurred, continued compression at a slower rate is performed. Once the intercalary screw starts to Bend as shown proximally, or the patient develops pain with transport, the compression should be stopped.

Early use of this implant has resulted in various surgical considerations to improve the surgical technique and allow for the technology to be utilized in multiple surgical scenarios. Regardless of technical variations, the principles of distraction osteogenesis remain unchanged. The authors believe that having an all-internal intramedullary nail system that can perform distraction osteogenesis provides a valuable new tool that will become an increasingly important part of the management of critical bone defects.

6. Expert opinion

The use of the Precice BTN has the ability to solve multiple problems that are currently encountered when reconstructing large bony defects. In terms of external fixation, the BTN resolves the issues of pin tract infections, and therefore obviates the need for antibiotic usage when these occur. An all-internal option also improves the cosmesis of the procedure and prevents the adverse psychological effects that can occur from having a frame in place for a prolonged period of time. It also decreases the risk of contractures and scarring than can occur from pins traversing through the musculature. When compared to the use of a vascularized fibula, the BTN does not risk the morbidity of requiring a separate surgical site. The BTN can also be combined with a Masquelet procedure by preserving the induced membrane from a temporary spacer. As the understanding of the indications and techniques required to proficiently use the BTN increase, we believe that all-internal transport is likely to become the standard of treatment for intercalary bone reconstruction.

Currently, as the BTN is new, there are multiple areas for improvement in the technology, such as the limitations of where an intercalary screw can be placed based on nail design. As seen in Figure 2, use of a cable can overcome this limitation. Recently, a trifocal tibial transport was described with a standard Precice nail using the PABST technique [28]. Further investigation will determine whether transport of multiple segments will be possible with the BTN. The main limitation of the technology is secondary to the strength of the implant which determines the size and location of the transport windows and the ability to weight bear. The materials available for implantation into humans is currently the main factor preventing this technology from advancing.

There is a wide range of future research possibilities with this implant. The optimal transport rate to form regenerate has not been defined. Functional and long-term outcomes have yet to be described and will be essential to prove the superiority to other techniques. Although all-internal transport has been described with the PABST technique, the implants differ, and long-term and functional outcomes are still lacking. Also, whether or not compression with docking alone versus the use of bone grafting or other technique is needed to obtain union will need to be delineated.

The future of intercalary bone reconstruction is likely limitless as technology, biologics and surgical techniques improve. The progression for distraction osteogenesis techniques is increasing significantly with the advent of all-internal techniques. As technology continues to improve, the principles of distraction osteogenesis should continue to be applied to continue to create better techniques.

It is likely that all-internal bone transport will become the standard for distraction osteogenesis in the next five to ten years. With newer technology, nails will likely be able to be programmed to transport at a rate individualized to the patient to form regenerate without the patient needing to use an external magnet. Techniques to help eradicate and prevent infection from open fractures will continue to progress and use of an antimicrobial coating on the nail will likely be an option. There will also likely be a way to easily lengthen the limb, correct and prevent deformities and transport multiple segments of bone. The field of all-internal distraction osteogenesis has been significantly advanced in the last ten years and will continue to progress as long as research and innovation is maintained.

Declaration of Interest

LM Zuckerman is a paid consultant and paid speaker for NuVasive Specialized Orthopedics; and has received research support from Onkos Surgical. JA Scolaro is a paid consultant for NuVasive Specialized Orthopedics, Smith &

Nephew, Stryker and Zimmer; and receives royalties from Globus Medical. MP Gardner is a paid consultant and speaker for NuVasive Specialized Orthopedics and DePuy; and receives research support from Zimmer. T Kern is a paid consultant and speaker for NuVasive Specialized Orthopedics and Stryker. P Lanz is a paid consultant for NuVasive Specialized Orthopedics. SM Quinnan is a paid consultant for NuVasive Specialized Orthopedics, Biocomposites, Bone Support, Depuy, Globus Medical, Microbion, Smith & Nephew, and Stryker; and receives royalties from Globus Medical. JT Watson is a paid speaker for NuVasive Specialized Orthopedics, Smith & Nephew and Zimmer; is a paid consultant for Smith & Nephew and Bioventus; and receives royalties from Arthrex, Inc., Biomet, NuVasive Specialized Orthopedics and Smith & Nephew. JD Rölfing is a paid speaker for Orthofix, Inc. The authors have no other relevant affiliations or financial involvement with any organization or entity with a financial interest in or financial conflict with the subject matter or materials discussed in the manuscript apart from those disclosed.

Reviewer disclosures

Peer reviewers on this manuscript have no relevant financial or other relationships to disclose.

ORCID

Lee M Zuckerman http://orcid.org/0000-0001-7762-2906

References

Papers of special note have been highlighted as either of interest (•) or of considerable interest (••) to readers.

1. Eralp L, Kocaoglu M, Rashid H. Reconstruction of segmental bone defects due to chronic osteomyelitis with use of an external fixator and an intramedullary nail. Surgical technique. J Bone Joint Surg Am. 2007;89(Suppl 2):183–195.
2. 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(12):1673–1680.
   • This article provides a systematic review of the results of the Ilizarov technique for distraction osteogenesis
3. Dahl MT, Green SA. Intramedullary limb lengthening: principles and practice. 1st ed. Switzerland: Springer International; 2018.
4. Masquelet A, Kanakaris NK, Obert L, et al. Bone repair using the masquelet technique. J Bone Joint Surg Am. 2019;101(11):1024–1036.
5. Paley D, Maar DC. Ilizarov bone transport treatment for tibial defects. J Orthop Trauma. 2000;14(2):76–85.
6. Rozbruch SR, Pugsley JS, Fragomen AT, et al. Repair of tibial nonunions and bone defects with the Taylor Spatial Frame. J Orthop Trauma. 2008;22(2):88–95.
7. Quinnan SM, Lawrie C. Optimizing bone defect reconstruc tion-balanced cable transport with circular external fixation. J Orthop Trauma. 2017;31(10):e347–e355.
8. Bas A, Daldal F, Eralp L, et al. Treatment of tibial and femoral bone defects with bone transport over an intramedullary nail. J Orthop Trauma. 2020;34(10):e353–e359.
9. Watson TJ. Distraction osteogenesis. J Am Acad Orthop Surg. 2006;14(Supplement):S168–74.
   • This article provides a good review of the traditional methods for distraction osteogenesis
10. Giotakis N, Narayan B, Nayagam S. Distraction osteogenesis and nonunion of the docking site: is there an ideal treatment option? Injury. 2007;38(Suppl 1):S100–107.
11. Antoci V, Ono CM, Antoci V Jr, et al. Pin-tract infection during limb lengthening using external fixation. Am J Orthop (Belle Mead NJ). 2008;37(9):E150–154.
12. Jauregui JJ, Bor N, Thakral R, et al. Life- and limb-threatening infections following the use of an external fixator. Bone Joint J. 2015;97(B(9)):1296–1300.
13. Aktuglu K, Erol K, Vahabi A. Ilizarov bone transport and treatment of critical-sized tibial bone defects: a narrative review. J Orthop Traumatol. 2019;20(1):22.
14. Liu Y, Yushan M, Liu Z, et al. Complications of bone transport technique using the Ilizarov method in the lower extremity: a retrospective analysis of 282 consecutive cases over 10 years. BMC Musculoskelet Disord. 2020;21(1):354.
15. Patterson M. Impact of external fixation on adolescents: an integrative research review. Orthop Nurs. 2006;25(5):300–308.
16. Wang H, Wei X, Liu P, et al. Quality of life and complications at the different stages of bone transport for treatment infected nonunion of the tibia. Medicine (Baltimore). 2017;96(45):e8569.
17. Barinaga G, Beason AM, Gardner MP. Novel surgical approach to segmental bone transport using a magnetic intramedullary limb lengthening system. J Am Acad Orthop Surg. 2018;26(22): e477–e482.
18. Quinnan SM, Seiter M. Femoral Bone Transport With a Combined Method Using a PRECICE Nail and Cable Lengthening Technique. J Orthop Trauma. 2018;32:e1–e8.
19. Olesen UK, Nygaard T, Prince DE, 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(8):e064.
   •• This article describes how to perform the PABST technique in detail and is applicable to bone transport using the Precice technology
20. Kähler Olesen U, Herzenberg JE. Bone Transport with Internal Devices. Tech Orthop. 2020;35(3):219–224.
21. Mikužis M, Rahbek O, Christensen K, et al. Complications common in motorized intramedullary bone transport for non-infected segmental defects: a retrospective review of 15 patients. Acta Orthop. 2021;92(4):485–492.
22. Vercio RC, Shields TG, Zuckerman LM. Use of Magnetic Growing Intramedullary Nails in Compression During Intercalary Allograft Reconstruction. Orthopedics. 2018;41(6):330–335.
23. Marais LC, Ferreira N. Bone transport through an induced membrane in the management of tibial bone defects resulting from chronic osteomyelitis. Strategies Trauma Limb Reconstr. 2015;10 (1):27–33.
24. Ferner F, Lutter C, Dickschas J. Retrograde bone transport nail in a posttraumatic femoral bone defect. Unfallchirurg. 2021;124 (5):412–418.
25. 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(3):199–205.
   •• This article provides tips and tricks on how to place blocking screws which is essential when using the BTN
26. Quinnan SM. Segmental Bone Loss Reconstruction Using Ring Fixation. J Orthop Trauma. 2017;31(Suppl 5):S42–S46.
27. 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. 2021;141(6):899–905.
28. Hwang J, Sems S, Yuan B. Trifocal tibial bone transport using a magnetic intramedullary nail: a case report. JBJS Case Connect. 2021 Oct 27;11(4):e20.01036.