Preliminary outcomes of a novel metal-coated antibacterial nail in Bone Transport Over Nail (BTON) and Nail After Bone Transport (NABT) procedures in cases of segmental infected tibial bone defects

ABSTRACT

Objective: To evaluate the clinical outcomes of a novel hybrid bone transport technique using an antibacterial-coated nail for the treatment of infected segmental tibial bone defects.

Methods: This retrospective study included 19 patients with infected segmental tibial bone defects treated using hybrid bone transport with an antibacterial-coated nail, the ZNN™ Bactiguard® nail. Patients were divided into two groups: nailing after bone transport (NABT, n = 11) and bone transport over nail (BTON, n = 8). These groups were compared with a control group of 10 infected patients treated with conventional external fixation bone transport (EFBT). The primary endpoint was infection eradication, while secondary endpoints included external fixation time (EFT), external fixation index (EFI), complications, and bone regeneration quality.

Results: The mean external fixation time (EFT) for the entire cohort was 280.2 ± 142.7 days. The BTON group had the shortest EFT (150 ± 45 days), significantly lower than both NABT (279 ± 99 days) and EFBT (927 ± 1710 days, p = 0.001). The external fixation index (EFI) was also significantly lower for BTON compared to EFBT (25 ± 10.7 vs. 77.5 ± 38.7 days/cm, p = 0.009). A single case of a recurrent infection was reported in the BTON group (5.3%), which was managed with nail removal and the continuation of external fixation bone transport without further complications. The infection was fully resolved in all cases (29/29) at the end of the follow-up period. Complication rates were similar across groups. The primary docking site union rate was 89.7%, with no significant differences between groups.

Conclusions: The BTON technique using an antibacterial-coated nail reduces EFT by threefold compared to traditional external fixation bone transports methods, without increasing complications. A notable reduction was also observed in the NABT group, although it did not reach statistical significance. This approach offers a promising alternative to conventional methods for the treatment of infected tibial bone defects.

Keywords: Bone defect, Fracture-related infection, Bone Transport, Ilizarov technique, Truelok, Intramedullary Nail, infection complications, Bactiguard.

INTRODUCTION

The tibia is frequently subjected to severe trauma, with an incidence of tibial shaft fractures reported between 8.1 and 37 cases per 100,000 person-year, 25% of which are open [1]. Significant bone loss may occur either directly from the trauma or as a result of subsequent surgical debridement due to infection. Successfully reconstructing these critical-sized defects is one of the most challenging tasks in orthopaedic and trauma surgery.

Current biological techniques for reconstructing such massive bone defects can be broadly categorized into bone-replacement techniques (such as the induced membrane technique and microsurgical bone flaps) and bone-regeneration techniques, primarily based on distraction osteogenesis [2]. For segmental bone defects following infection in the adult lower limb, distraction osteogenesis techniques using external fixation devices are commonly preferred [3]. However, bone transport for infected bone defects is a complex and prolonged procedure. In adult patients with segmental tibial defects, the average external fixation index (EFI) ranges from 1.5 to 2.5 months per centimetre with classical external fixation techniques [4]. Such prolonged external fixation time (EFT) is a major drawback, significantly impacting patient function, quality of life, and emotional well-being. Additionally, longer EFT is associated with a time-dependent increase in complications [5].

Hybrid bone transport techniques, which combine external fixation with internal devices, have been developed to address these challenges. Specifically, using an intramedullary nail in combination with a circular external fixator has the potential to dramatically reduce EFT and its associated complications [4,6]. However, the transcutaneous nature of external fixation pin sites—without an intact physiological skin barrier throughout the duration of external fixation—presents an inherent risk of internal hardware infection.

Recently, a noble-metal alloy-coated titanium intramedullary nail, containing silver, gold, and palladium (ZNN™ Bactiguard® nail; Zimmer-Biomet®, Warsaw, Indiana, USA), has become available in the orthopaedic arsenal [7,8]. This non-eluting coating technology is based on a galvanic effect activated upon contact with moisture, generating pico-currents (trillionths of an ampere, 10^{-12} A) on the implant surface. These pico-currents reduce microbial adhesion and biofilm formation on the coated surfaces [9], thereby lowering the risk of infection. Initially, this prophylactic nail was indicated for stabilising tibial fractures with high-risk of infective complications, such as open fractures, closed fractures with compromised soft tissue or immunodepressed patients [7,8]. Furthermore, the 'self-protecting' characteristics of this technology make it particularly attractive for use in combination with external fixation.

The purpose of this study is to describe an established hybrid bone transport protocol for the reconstruction of infected tibial bone defects using such antibacterial-coated nail in either Bone Transport over Nail (BTON) or Nailing after Bone Transport (NABT) strategies. The primary endpoint is to analyse the rate of recurrent infections and nail-related complications. The secondary objective is to investigate whether the BTON or NABT techniques reduce EFT or EFI compared to a matched cohort undergoing classical circular frame bone transport. The hypothesis is that both hybrid techniques are associated with shorter EFT without an increase in complications.

MATERIAL AND METHODS

This is a non-interventional, retrospective, single-centre cohort study. After obtaining institutional review board (IRB) approval, we conducted a retrospective review of our prospectively accumulated institutional database to identify all patients with infected tibial bone defects treated under a hybrid bone transport protocol using a ZNN™ Bactiguard® nail (Zimmer-Biomet®, Warsaw, Indiana, USA) between January 2021 and June 2023. Our centre is a 1,000-bed tertiary university hospital that houses a national referral musculoskeletal infection unit. Additionally, a matched control group of infected patients treated with classical circular frame bone transport during the same study period was randomly selected from the database. Patients were divided into three cohorts based on treatment modality: (a) Bone Transport over Nail (BTON), (b) Nailing after Bone Transport (NABT), and (c) External Fixation Bone Transport (EFBT). All patients received information about the study and signed an informed consent form.

The inclusion criteria were as follows: (a) adult patients (>18 years old), (b) infected tibial bone defect, (c) bifocal circular fixation (single osteotomy) bone transport, (d) use of the ZNN™ Bactiguard® nail in the BTON and NABT groups, and (e) a minimum follow-up of 12 months after completing the bone transport procedure. Patients who did not meet the inclusion criteria were excluded from the study.

All included patients had a confirmed diagnosis of deep infection according to internationally accepted criteria [10]. Infection was diagnosed if at least one of the following criteria was fulfilled: (1) presence of a sinus tract, (2) exposure of bone or osteosynthesis material, (3) positive histology, (4) presence of pus or intraoperative abscess, or (5) ≥2 positive cultures with the same pathogen. Cases were classified according to the FRI classification, which considers Fracture severity, Related patients factors and Impairment of soft tissues [11,12]. Regarding infection eradication criteria, at the time this study was conducted, no internationally accepted definition for FRI-treatment success or failure were available. To address this limitation, standardise our results, and avoid subjective personal definitions, we instead adopted an internationally accepted definition of periprosthetic joint infection success. According to this definition, infection eradication was considered confirmed only if the patient met all of the following criteria [13]: (a) healed wound, (b) no recurrence of infection at one-year follow-up, (c) no subsequent surgical intervention due to infection, (d) no infection-related mortality, and (e) absence of suppressive antibiotic therapy. The following data were retrospectively collected: (a) demographics, (b) comorbidities (e.g. smoking, alcoholism, obesity, diabetes), (c) injury characteristics (Gustilo classification, bone defect length [cm], soft tissue defect, microbiological data), (d) bone transport modality (BTON, NABT, or EFBT), (e) regenerate bone quality was assessed according to the radiographic classification proposed by Li et al. [14], which categorises the regenerated bone as atrophic (low density), hypotrophic (intermediate density), and normotrophic (normal density) (f), external fixation time (EFT) and external fixation index (EFI), (g) complications, and (h) duration of follow-up. EFI was defined as the number of days in external fixation per centimetre of regenerated bone length gained (days/cm) [15].

Operative Technique Description:

All surgeries were performed by the senior surgeon (P.C.), adhering to a standardised surgical protocol as outlined below. Patients with infected tibial defects now typically undergo a single-stage procedure, a practice increasingly favoured in recent years, unless a persistent nail infection or the need for a microsurgical flap to reconstruct the soft tissue defect is present [2]. In such cases, a stepwise approach is followed: the nail is removed, the intramedullary canal meticulously debrided, and an antibiotic-loaded cement spacer is inserted into the bone defect. Additionally, an intramedullary antibiotic-loaded calcium sulphate carrier (Stimulan™ Bullet Mat;

Biocomposites Ltd, Staffordshire, England) is applied. Temporary stabilisation of the tibia is achieved using a spanning all-wire circular frame (Truelok®; Orthofix, Sommacampagna, Verona, Italy or Clickit®-CF, Mikai S.p.A, Genova, Italy).

The definitive reconstructive surgery is performed with the patient in the supine position under a sterile tourniquet (Hemaclear™; OHK Medical Devices, Haifa, Israel). The initial phase of the procedure prioritises infection eradication, focusing on thorough surgical debridement and the removal of all contaminated hardware, as well as devitalised bone and soft tissue. Multiple samples are obtained for culture and histological analysis before administering antibiotics. The bone ends are cut orthogonally to the tibial axis in both coronal and sagittal planes to ensure precise alignment and optimal healing at the docking site. Bone viability is confirmed following tourniquet release by observing punctate bone bleeding, commonly referred to as the Paprika sign.

Following thorough debridement and irrigation, one of three techniques—BTON, NABT, or EFBT—was selected based on patient-specific factors. In general, the BTON technique was chosen for patients with septic segmental bone defects not associated with an active nail infection, provided that the soft tissues were either intact or had been successfully reconstructed. Ideally, no external half-pins should be present at the time of nailing. For patients with an ongoing nail infection, compromised soft tissue, or infected half-pin sites, a staged approach was preferred, delaying tibial nailing (NABT) until all these issues had been resolved. In cases where the proximal or distal bone segments were insufficient or structurally weakened, precluding stable nail fixation, a classical bone transport technique was employed. A single design of circular external fixator (Truelok®; Orthofix, Sommacampagna, Verona, Italy) was used in all cases.

A. **External Fixation Bone Transport (EFBT):** The circular external fixator was applied using a standard technique as described elsewhere [16] . Typically, all-wire frames with tensioned fine wires (1.8 mm, tensioned to 100–130 kg) were used, with wires positioned as close to orthogonal angles as possible. Frame configuration was customized based on case specifics. The osteotomy was performed percutaneously using a Gigli saw (Afghan osteotomy) [17]. Distraction began 10–14 days postoperatively at an initial rate of 1 mm/day in four equal increments, later adjusted based on regenerate bone formation. Docking sites were routinely debrided and, in cases where the contact between bone edges was less than 75%, we added autologous bone graft to improve successful docking site healing. Patients were allowed to bear weight as tolerated using crutches or a walker. The external fixator was removed once docking site consolidation and regenerate bone maturity were achieved.

B. **Bone Transport Over Nail (BTON):** This technique utilized either anterograde or retrograde hindfoot nails. Nail size and length were determined intraoperatively, selecting the thickest nail suitable for the intramedullary canal. The antibacterial-coated nail was customized intraoperatively by adding two additional locking holes at the planned docking site of the transported bone segment to secure it and prevent recoil after frame removal (**Figure 1**). These holes were straightforwardly created using sequential high-speed steel (HSS) drill bits (DePuy Synthes, Oberdorf, Switzerland) in 2.5 mm, 3.5 mm, and finally 4.8 mm diameters. Routine over-reaming of 2 mm larger than the nail diameter was performed to allow the transported segment to move freely along the nail. For anterograde nails, a suprapatellar approach was typically used for nail insertion (**Figure 2**). During the study period, a dedicated ZNN™ Bactiguard® retrograde hindfoot nail was unavailable. To address this limitation, an anterograde nail was used in a retrograde fashion when necessary. In such cases, the nail's Herzog curve was oriented laterally to avoid ankle varus deformity, and a suprapatellar handle was employed (**Figure 3**). After performing a percutaneous osteotomy using a Gigli

saw, the nail was locked distally and proximally with interlocking screws. Once the wound was closed, a circular external fixator was applied in a standard fashion. Only all-wire frames were used, with tensioned fine wires (1.8 mm wires tensioned to 100–130 kg). Distraction began 14 days postoperatively, with a distraction rhythm of 0.75 mm/day divided into three equal increments. Upon achieving the docking site, the transported bone segment was locked in place with two 4.0 mm screws under fluoroscopic guidance, and the external frame was removed (**Figure 4**). The docking site was not routinely approached, only in cases where delayed healing was observed. Postoperatively, patients were allowed weight-bearing as tolerated on the affected limb using crutches or a walker during the circular fixation phase. After frame removal, partial weight-bearing was recommended until the regenerated bone matured.

C. **Nailing After Bone Transport (NABT):** The initial phase of this technique is identical to the EFBT method. All-wire circular frames are preferred for this strategy, as they allow direct nail insertion without requiring a "pin-holiday" period. In cases where 6-mm hydroxyapatite-coated half-pins are used, they must be removed at least two weeks prior to nailing. Once minimal healing of the docking site is observed, a reamed suprapatellar or retrograde ZNN™ Bactiguard® nail is inserted across the regenerate bone using standard techniques. Nailing is typically performed with the external fixation still in place to safeguard the immature, newly formed regenerate bone (**Figure 5**). Afterward, the external fixation is removed (**Figure 6**). The docking site was not routinely approached, only in cases where delayed healing was observed. Partial weight-bearing is recommended following nailing and continues until the regenerate bone has fully matured.

Follow-Up Protocol: Regarding antibiotic treatment, a case-by-case decision-making process was employed to determine the appropriate antibiotics, route of administration, and treatment duration, under the guidance of a team of experts in musculoskeletal microbiology and infectious diseases, who are integral members of our multidisciplinary committee. As a general principle, in cases where a pseudo-oncological approach with radical segmental resection was performed, the duration of antibiotic treatment typically spans 4 weeks, with a transition to oral antibiotics as soon as feasible, provided that antibiotics with good oral bioavailability and bone penetration are available.

Following the removal of external fixation, patients are discharged once soft tissue healing is deemed satisfactory. Follow-up appointments are scheduled at 2 weeks, and subsequently at 1-, 3-, 6-, and 12-months post-discharge. During these visits, clinical and radiological evaluations are performed to confirm complete maturation of the bone regenerate, ensure solid union, and rule out infection recurrence. Pin-wire site care includes an initial regimen of weekly cleaning with alcoholic chlorhexidine and occlusion with a bulky dressing. After 2–3 weeks, daily cleaning of the pin sites is introduced, and the sites are left uncovered. Patients are actively trained in self-management of pin-site care to ensure proper hygiene and reduce the risk of complications.

Statistical Analysis: Descriptive statistics were used to summarize cohort characteristics. Categorical variables were presented as absolute values and percentages, while continuous variables were expressed as means, standard deviations, and ranges. Normality was assessed using the Shapiro-Wilk test. Group comparisons employed the chi-squared test or Fisher's exact test for categorical data, and the Student's t-test, ANOVA, or Kruskal-Wallis test for continuous data, as appropriate. A p-value < 0.05 was considered statistically significant. Analyses were performed using R statistical software version 4.4.1 (R Development Core Team).

RESULTS

A total of 25 patients with infected tibial bone defects treated using a hybrid bone transport technique with an antibacterial-coated nail were identified. After excluding six cases due to incomplete follow-up, 19 cases were included in the analysis: 11 treated with nailing after bone transport (NABT) and 8 with bone transport over nail (BTON). These were matched with a control group of 10 infected patients treated with standard external fixation bone transport (EFBT), (Figure 7). Among the 29 cases of bone transport, 28 patients were male (96.6%), with a mean age of 47.9±13.2 years (range: 26–75 years). In all cases, the bone defect was caused by a tibial FRI. All of them were categorized as F4 according to the FRI Classification, since all the fractures were not healed and presented a major bone defect. Regarding the initial injuries, 79% were open fractures, and 59% required soft tissue reconstruction, with microsurgical free flaps performed in 82% of these cases (I4). The mean bone defect length after debridement was 6.6±2.7 cm. The cohorts were comparable, with no significant differences in baseline characteristics or risk factors (**Table 1**).

Open debridement of the docking site was performed in 17 patients (58.6%), being more frequent in the EFBT group (90% vs. 42%; p=0.04) (**Table 1**). There were no significant differences in the use of autologous bone grafting for the docking site among the three groups (11 patients; 37.9%). The primary docking site union rate was 89.7%, with no significant differences between groups (p=0.46). Regenerated bone quality was also similar across groups: 90% of cases were classified as normotrophic. One patient in the NABT group developed atrophic regenerate bone; this case was managed with NABT specifically to provide more stability, reducing the high risk of fracture associated with frame removal while benefiting from autograft deposition via sequential reaming.

Primary Study Outcome: Among the 19 cases treated with an antibacterial-coated nail (NABT and BTON groups), only one case of infection was observed (5.3%). This patient, in the BTON group, experienced necrosis of an anterolateral thigh flap during nail insertion, leading to nail exposure for four days until a new free flap was performed. Subsequently, the nail was removed, percutaneous intramedullary debridement was performed and targeted antibiotic therapy for methicillin-sensible *S. aureus* was administered. The treatment was converted to a standard EFBT, which resolved the issue without recurrence. No infection was observed in the NABT and EFBT groups. Infection eradication, as defined by internationally accepted criteria, was achieved in all cases (29/29) after a mean follow-up of 27.7±11.4 months (range: 13–47 months).

Complication rates were comparable across groups (p=1). Beyond the aforementioned infection, two additional bone transport related complications were observed (**Table 2**). One patient in the NABT group experienced nail breakage (not related to custom nail holes) associated with docking site non-union 10 months post-insertion. It was resolved with nail removal, non-union site debridement, autologous grafting, and reinsertion of a new tibial nail, achieving union without further issues. Another patient in the EFBT group suffered a fracture of the regenerate bone one week after frame removal, which was managed with repeated circular fixation for five months. No adverse effects or allergic reactions related to the Bactiguard® noble-metal coating or the customized nail holes were observed. Among the six excluded cases with incomplete follow-up, no infections or complications were noted during the study period.

Secondary Study Outcome: Table 3 summarizes the external fixation time (EFT) and external fixation index (EFI) across the groups. The mean EFT for the entire cohort was 280.2±142.7 days. EFT differed significantly among groups: EFBT had the longest mean EFT, followed by NABT, with BTON having the shortest (927±1710 vs. 279±99 vs. 150±45 days; p=0.001). The mean EFI for the entire cohort was 50.5±35.7 days/cm. Significant differences in EFI were observed between EFBT and BTON (77.5±38.7 vs. 25±10.7 days/cm; p=0.009), demonstrating that BTON reduces time in external fixation by nearly threefold compared to standard external

fixation. Although NABT had a shorter EFI compared to EFBT (44.4±29.2 vs. 77.5±38.7 days/cm) and a longer EFI compared to BTON (44.4±29.2 vs. 25±10.7 days/cm), these differences did not reach statistical significance, likely due to limited statistical power.

Discussion:

This preliminary study on 19 patients with infected segmental tibial bone defects treated via hybrid bone transport using a novel metal-coated antibacterial nail demonstrates several significant findings. We observed a considerable reduction in external fixation time (EFT) compared to traditional external fixation techniques, underlining the potential advantages of combining internal and external fixation. Importantly, this reduction in EFT occurred without an increase in complications, particularly infections, thus supporting our initial hypothesis. To the best of our knowledge, this is the first study to report clinical outcomes using such antibacterial nail for managing extensive infected tibial bone defects.

Reconstruction of critical-sized bone defects is among the greatest challenges in orthopaedic and trauma surgery, particularly when compounded by infection [2]. Management requires aggressive debridement of necrotic bone and soft tissue, often resulting in extensive defects that necessitate both bone reconstruction and soft tissue coverage. Distraction osteogenesis using external fixation devices offers unique advantages in infected cases, including minimal soft tissue disruption, effective management of large defects, and low rates of infection relapse [16]. However, prolonged external fixation remains a primary drawback, negatively impacting patients' quality of life and increasing complication risk [5]. Reducing EFT is, therefore, a crucial objective to improve patient satisfaction and outcomes. Several techniques modifications have been proposed in an attempt to decrease the time that patients have to wear the cumbersome external fixation, as the trifocal bone transport [18], use of orthobiologics technologies [19], all-internal bone transport combining lengthening nails and plates or bone transport nails [20]. Hybrid bone transport techniques, combining external fixation with internal stabilization devices like plates or nails, have emerged as a promising solution for reducing EFT. Prior studies have predominantly focused on length discrepancy corrections using methods such as Lengthening and Then Nailing (LATN) or Lengthening Over Nail (LON), which differ significantly from managing infected tibial defects [21]. Our literature review identified few studies examining the use of intramedullary nails in combination with external fixators for severe infected bone loss. The use of intramedullary nails in infected cases remains controversial due to concerns about introducing implants into a high-risk septic environment. For instance, Song et al. reported a 14% deep infection rate in femoral lengthening over a nail, highlighting this risk [22]. In a retrospective study of 36 patients with tibial segmental bone defects treated using Bone Transport Over Nail (BTON) or Bone Transport Over Plate (BTOP), the authors reported significantly lower EFI for BTOP than BTON (0.45 vs. 0.94 months/cm; $p < 0.01$) [23]. However, one BTON patient experienced deep infection of the regenerated bone, resulting in reconstruction failure. The longer EFI in BTON was attributed to the lack of nail customization, requiring prolonged external fixation until docking site healing. In another retrospective series of 40 cases involving two-stage BTON (19 femoral and 21 tibial defects), intramedullary nail removal, debridement, and insertion of antibiotic-impregnated rods were necessary in four cases (three tibial and one femoral) [4].

One key finding of our study is the remarkably low rate of nail-related infections, with only one case (5.3%) observed in the BTON group, which was resolved by conversion to standard external fixation. The hybrid bone transport strategies using an antibacterial-coated nail significantly reduced EFI compared to traditional Ilizarov bone transport technique without increasing septic complications. Additionally, we demonstrated that a single-stage surgical approach with meticulous debridement is safe. However, we recommend a two-stage approach for cases with ongoing nail infections. Consequently, this innovative approach has now become the standard of care in our specialised unit.

Our findings align with those of Xu et al., who compared BTON in combination with an antibiotic-loaded resorbable carrier to conventional external fixation in infected tibial defects [24]. They also reported a significant reduction in EFT without an increase in

deep infection rate. However, their reliance on antibiotic-loaded calcium sulphate raises concerns about long-term nail protection. Antibiotic carriers typically release their payload within days to weeks, which may leave the nail unprotected for much of the bone transport procedure. The same concern applies to the gentamicin-coated Expert Tibia Nail (ETN) PROtect® (DePuy Synthes, Oberdorf, Switzerland). It provides an initial burst of antibiotic release within the first 12–24 hours, which may be insufficient to protect the nail over extended treatment periods [25,26]. Furthermore, there are concerns about the effectiveness of gentamicin-only coatings. In contrast, the noble metal-coated technology used in our study aim to ensure sustained antibacterial activity throughout the treatment period, avoiding antibiotic resistance and maintaining consistent protection [7–9].

Despite the inherent risks of intramedullary nailing after prolonged external fixation, we observed no infections in the Nailing After Bone Transport (NABT) group when adhering to our strict exchange protocol. Historically, this risk has been well-documented when intramedullary nails are inserted following external fixation for high-energy trauma or open tibial fractures [27,28]. For instance, a recent series of 88 acute extra-articular tibial fractures treated with provisional external fixation followed by intramedullary nailing reported a 32% deep infection rate [27]. As expected, longer external fixation durations correlated with higher infection risks (RR: 2.67; $p = 0.003$). The mean external fixation time in that series was only 9 days (range: 1–61 days), vastly different from NABT strategy, where external fixation can persist for weeks to months. Two factors likely contributed to our outcomes: (1) our preference for all-wire external fixation frames, which reduce soft tissue irritation-infection and facilitate subsequent nail insertion without the need for prolonged “pin holidays” and (2) the antibacterial coating technology of the ZNN™ Bactiguard® nail. Based on these results, we recommend using all-wire frames in BTON and NABT procedures.

Concerns regarding endosteal vascular disruption and docking site complications were also addressed. We found no differences in regenerated bone quality between the BTON and EFBT groups, suggesting that the enhanced stability provided by the intramedullary nail offsets any potential vascular disruption. Additionally, the need for docking site debridement and grafting was significantly lower in the BTON group, likely due to improved mechanical stability and reduced medullary canal closure.

We acknowledge some limitations in our study. First, its retrospective nature introduces potential biases due to reliance on medical records, which may lack critical data. Second, the absence of a control group using alternative nails limits direct comparisons. Third, the small sample size reduces statistical power and the ability to detect rare complications. Lastly, the study was conducted at a single, high-volume specialized centre, which may limit generalizability to less experienced settings. Nonetheless, the consistency of our protocol and meticulous follow-up enhances the study’s validity. Prospective studies with larger sample sizes, multi-centre participation, and extended follow-up are essential to confirm these findings and refine the use of antibacterial-coated nails in hybrid bone transport. Such research will provide a more comprehensive understanding of the long-term efficacy and safety of this approach.

Conclusions:

This study highlights the effectiveness and safety of the hybrid bone transport technique using an antibacterial-coated nail for infected segmental tibial defects. This strategy significantly reduced external fixation time compared to traditional external fixation bone transports methods. Furthermore, it did not associate an increase in complications, particularly infection.

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Figure Legends:

Figure 1: Intraoperative picture showing a segmental tibial defect (left-ankle and right-knee). Custom modifications in the ZNN™ Bactiguard® nail at the planned docking site of the transported bone segment. The two additional 4.8 mm holes are designed to secure the segment and prevent recoil after external frame removal.

Figure 2 (a/b): Panel illustrating the BTON procedure using an antibacterial-coated nail. (A) Suprapatellar approach used for anterograde intramedullary nail insertion. (B) Application of a simple all-wire circular external fixator to perform controlled bifocal bone transport.

Figure 3: Retrograde insertion of the nail using the suprapatellar handle. This technique allows an anterograde nail to be inserted retrogradely, facilitating ankle fusion at the docking site. The nail's Herzog curve was oriented laterally to avoid ankle varus deformity

Figure 4 (a/b/c): Radiographic sequence illustrating the BTON procedure using an antibacterial-coated nail. (A) Bone transport phase where the nail enhances navigation and construct stability. (B) Locking the transported bone segment at the docking site using two 4.0 mm screws, with the addition of a plate for increased stability and compression in this specific case, followed by frame removal. (C) Final radiograph showing solid fusion at the docking site and normotrophic regenerated bone.

Figure 5: Nail After Bone Transport (NABT) procedure using a suprapatellar antibacterial-coated nail. Nailing is performed while the external fixator remains in place to protect the immature regenerated bone.

Figure 6 (a/b/c): Radiographic sequence of the NABT procedure using an antibacterial-coated nail. (A) Initial phase with a classical all-wire circular frame for bone transport. (B) Conversion to an intramedullary nail once the docking site shows early consolidation, without a pin-holiday period. (C) Final radiograph displaying solid docking site fusion and normotrophic regenerated bone.

Figure 7: Flowchart of the study.