Reconstruction of traumatic composite bone and soft tissue loss (TCBSTL) employs several approaches among which is the bone transport (BT). In this procedure a healthy bone segment is mobilized by means of an external fixator to bridge a bone gap. Mobilization of the bone segment entails advancement of the overlying soft tissue envelop altogether. Between the year 2000 and 2017 the authors have treated 150 cases of TBSTL using distraction histogenesis and external skeletal fixation in all cases. The procedure was performed in two modes, in the first group the transport was performed gradually by distraction-compression of the osteotomy and bone defect sites respectively. In the second group, the procedure was performed by acute shortening and re-lengthening (ASRL) technique. Skin grafts(STSG)were used in six cases (4%) and iliac crest bone graft(ICBG) in 42 cases (28%). No free vascularized tissue grafts were used in any case. No internal fixation was attempted in any case. A few problems have been met with during gradual bone transport, and were manageable without effect on the treatment course or final outcome. Based on our observations in this series, BT was defined as “Bone transport is an instrumented advancement of a local vascularized osteomyocutaneous flap to bridge bone and soft tissue defect either gradual or acute.” When perceived as an osteomyocutaneous flap, bone transport extends the umbrella of the reconstruction ladder to include cases where other procedures could not be safely employed. Bone transport, either gradual or acute, is a powerful tool in the armamentarium of Orthoplastic limb reconstruction.

Keywords: bone and soft tissue loss; leg trauma; Ilizarov; bone transport; orthoplastic
ance to the technique and cases that could be managed by simpler techniques were excluded from the study. Specific national laws have been observed and patients’ informed consent has been obtained.

Distraction histogenesis and external skeletal fixation were used in all cases. The study cases were carefully allocated to either mode of composite tissue transport [gradual distraction – compression (GDC) or acute limb shortening and re-lengthening (ASRL)]. The choice of either method was based on adequacy of limb blood supply, size of defect and level of bone defect [8].

Preoperative evaluation
Preoperative counseling of the patient and his caregivers was carried out with the aim of explaining the intended procedure and the expected difficulties to ensure the patient’s cooperation and the support of his family. The smoker patients were requested to quit smoking before embarking on the procedure. General clinical examination of the patient was done to exclude the presence of general debilitating or systemic illness. The limb was examined for the neurovascular status, skin condition, shortening, range of motion of adjacent joints and evidence of active infection (draining sinus, local inflammation, pain, tenderness, swelling and elevated ESR and CRP). Radiographs of the limb were obtained and examined for the level and size of bone defect, bone quality, leg shortening, and the condition of nearby joints. Difficulty indicators in every case scenario were defined (Table 1) [7].

Gradual Distraction-Compression (GDC)
This procedure was performed whenever ASRL was not feasible due to long segment bone and soft tissue loss, vascular compromise e.g. single artery limb or multiple longitudinal scars of previous surgery. The fracture-site was debrided to excise all infected and devitalized tissue with a safety margin of at least 5 mm. (oncological debridement) [18–21]. All retained hardware was removed. “Square osteotomy” of the bone ends was performed, except with very short distal bone segments, to increase the bone contact surface area at the docking site. The osteotomy was performed so that the bone ends were cut shorter than the skin edge which is hanging, like a curtain, to cover the bone ends (soft tissue curtain) (Figure 1). A percutaneous, multiple drill holes and osteotome, osteotomy was performed in the metaphysis farthest from the fracture site. Incremental distraction of the osteotomy and compression of the bone gap was performed at a rate of one mm. per day starting 5 – 7 days postoperatively. Distraction-compression was continued until the tissue gap was obliterated and the bone ends came to contact (Figures 2 and 3). Revision of the docking site was performed, if needed, to excise excess skin insinuated between bone ends, to improve bone contact or to insert bone graft in case of poor bone contact [4] (Figure 4).

Figures 5 and 6 present a clinical case demonstration of local tissue transport.

Acute Shortening and Re-Lengthening (ASRL)
This procedure was performed when the tissue gap allowed acute limb shortening without vascular compromise (Figure 7). The skin incision was Z-shaped with the horizontal limb centered on the area of unhealthy skin and infected sinuses. This horizontal limb of the incision was converted into an ellipse to excise unhealthy tissues. Transposition of the skin ends allowed transformation of the long narrow tissue tube into a shorter and wider one to accommodate the crowded tissues after limb shortening [8, 22]. Adaptation of the bone ends was performed for best bone contact and insertion of bone graft if indicated (Figures 8 and 9).

Table 1: Preoperative difficulty indicators [7].

| Preoperative difficulties                      | N    | %    |
|------------------------------------------------|------|------|
| Comorbidities (diabetes mellitus, obesity)     | 32 cases | 22   |
| Smoking patient                                | 90 cases | 60%  |
| Leg length discrepancy                         | 1–11 cm | Average 4.3 cm |
| Deformity (oblique plane)                      | 10–35° | Average 27°   |
| Ankle joint stiffness                          | 12 cases | 8    |
| Level of fracture                               |      |      |
| · Upper third                                  | 28 cases | 19   |
| · Middle third                                 | 84 cases | 57   |
| · Lower third                                  | 36 cases | 24   |
| · Ankle                                        |      |      |
| Active infection                                | 109 cases | 72.6 |
| Bone loss                                      | 1–13 cm | Average 5.2 cm |
| Equinus contracture (>5°)                      | 29 cases | 20   |

Distribution of the study cases according to the preoperative difficulty indicators.
Ilizarov frame for external skeletal fixation was used in all cases.

**Postoperative management**

Postoperative leg elevation was necessary to avoid postoperative edema. Active non-weight-bearing exercises of the limb were encouraged as soon as postoperative pain had settled. Weight-bearing as tolerated was allowed throughout the treatment. Patients were seen in the clinic every two weeks during the distraction phase (to check for soft tissue problems during transport) and then every month during the consolidation phase. Radiographs were obtained in each visit to check the progress of bone transport and healing. The external fixator was removed after bone consolidation. Criteria for bone consolidation and safe removal of the external fixator have been: 1) radiological: at least three intact bone cortices and radiological density of the regenerate bone comparable to adjacent normal bone. 2) clinical: the “single – leg stance test” (the patient should be able to stand unsupported on the

**Figure 1:** Diagrammatic demonstration of the three keys to successful debridement of infected nonunion in preparation for tissue transport: 1) oncological debridement entails excision of all devitalized tissues, 2) square osteotomy of bone ends so as to maximize bone contact area at the time of docking which would obviate the need for bone grafting, 3) soft tissue curtain to avoid desiccation of exposed bone and to ensure skin healing by the time of bone contact so that no skin grafts would be needed.

**Figure 2:** Diagrammatic illustration of the technique of bifocal compression – distraction (gradual bone transport) to bridge a combined bone and soft tissue defect.
treated limb for 30 seconds) to consider the bone consolidated to allow safe removal of the external fixator. No CT or Ultrasound examinations were performed, to evaluate consolidation of regenerate bone.

After fixator removal, a well-fitted plaster cast was applied for one month with weight-bearing. Patients were then followed up every three months and then yearly.

**Evaluation of treatment outcome**

The results were assessed based on both objective (clinical and radiographic evaluation) and subjective criteria (limb function and patient’s satisfaction) using our system of results' evaluation (Table 2) [8]. This included the evaluation of bony union, residual deformity, residual leg length discrepancy, recurrent infection, soft-tissue healing, permanent joint contracture, persistent pain, return to previous work, and patient satisfaction. The final results were considered to be satisfactory or unsatisfactory based on these findings using the summation of these values in all cases. To be considered as satisfactory, the case should fulfill all the criteria of satisfactory results. In cases of tibio-talar fusion, the position of the foot relative to the leg (plantigrade foot) and soundness of the fusion were evaluated instead of the ankle range of motion.

**Figure 3:** a) clinical photo of an open fracture of distal leg, heavily contaminated with sewage disposal water, after debridement of all unhealthy tissues including 4 cm. of tibial bone. b) the same wound after completion of tissue transport. The skin healed with no residual infection. No soft tissue grafts needed. c) and d) radiographs after surgery and at the end of transport show consolidation of 4 cm proximal regenerate and solid union at the docking site distally. No bone grafts were needed.

**Figure 4:** Invagination of excess skin a), between the bone ends at the docking site b), which necessitate revision of the docking site to excise this excess skin c).
Results

Table 3 summarizes the results of the study cases

In this study, 150 patients were treated for post-traumatic composite bone and soft tissue loss (TCBSTL) of the leg and ankle. Their ages ranged from 12 to 64 years (average, 36 years). There were 122 males (81%) and 28 female (19%) patients. There was previous surgical treatment using different techniques for bone and soft tissue reconstruction in 27 cases (18%). The number of procedures per case ranged from one to five (average, 2.1 procedures/case). Active infection was present in 109 cases (72.6%); out of these cases: 34 patients (22.6%) had retained hardware, infected open fracture in 45 cases (30%) and infected nonunion after previous surgery but no retained hardware in 30 cases (20%). Ilizarov external fixator was used in all cases. Gradual distraction–compression (GDC) was performed in 103 cases (68.7%) while acute shortening and re-lengthening (ASRL) in 47 cases (31.3%). Autogenous iliac crest bone graft (ICBG) was performed in 42 cases (28%). Split thickness skin graft was needed in six cases (4%) to cover residual skin defect. Frequent superficial pin tract infection occurred in all cases, especially during the phase of distraction, and was treated by daily pin site care and oral antibiotics. Revision of the docking site was needed, in 114 cases (76%), at the end of transport to clear out the invaginated skin between the bone ends,

Figure 5: a) radiograph of open pilon fracture grade IIIB, initially treated by multiple Kirschner wires and monolateral external fixator. b) debridement included square osteotomy of the distal tibia to remove devitalized bone (9.5 cm). c) modest acute shortening was performed due to traumatic vascular injury. Proximal tibial osteotomy for transport and leg lengthening. d) final outcome radiograph shows solid tibio-talar fusion and consolidated proximal regenerate 9.5 cm.

Figure 6: Clinical photos of the case in figure 5. a) at the time of presentation; shows extensive skin and bone loss. b) during treatment; soft tissue approximation is in progress together with distal bone transport. c) final outcome photo shows complete soft tissue healing. Foot in a plantigrade position. No bone or soft tissue grafts were used in this case.
to improve contact of bone ends or to insert bone graft (Figure 4). All patients completed the follow up which ranged from 24 to 118 months (average 35). No cases of recurrent infection were encountered during treatment or at follow-up. Equinus contracture of more than 10° developed in six cases (4%) and was treated by frame extension on the foot and gradual stretching aided by percutaneous achilles tenotomy. Limb lengthening was done in all cases and ranged from 4 to 11 cm (average 6 cm). Equalization of limb length was obtained in 141 cases (94%), and residual LLD more than 2.5 cm occurred in nine cases (6%). The main reasons for residual LLD were cessation of limb lengthening either due to the patient’s intolerance to the procedure or development of significant joint contracture. Fracture union was obtained in all cases (100%). No cases have developed vascular injury or ischemia due to treatment. No free vascularized tissue grafts were used in any case. No internal fixation was attempted in any case. Amputation was not needed in any case. The results were satisfactory in 141 cases (94%) and unsatisfactory in nine (6%) cases due to residual leg length discrepancy, joint stiffness, and persistent pain. Figures 8 and 9 present the results of both techniques (bone transport and acute shortening and re-lengthening).
Discussion
The management of TCBSTL remains a controversial subject because of the lack of clear guidelines regarding the most suitable treatment for each case scenario [1, 4, 12]. The combination of the problems of soft tissue loss, fracture/nonunion, deformity, infection, bone loss, and LLD renders traditional treatment protocols fraught with complications.

The reconstructive ladder and its variants have been all centered on soft tissue reconstruction and wound coverage, leaving bone reconstruction for a second stage. Such approach renders reconstruction technically demanding, lengthy and costly, which may urge the patient and treating surgeon to choose amputation rather than limb salvage [23].

The quality of debridement of bone infection is a key factor influencing infection, and hence of the outcome of any reconstructive approach [21]. Adjuvant antibiotic therapy may mask the effect of an inadequate debridement by suppressing but not eradicating any resultant infection [14]. Debridement of bone infection may result in bone and soft tissue defects. It may be acceptable to achieve primary closure of the wound by direct suturing or tissue transfer at the same sitting as the debridement. The management of bone defects is dependent on several factors including the host's physiological status, the size of the defect, level of the defect, quality of the surrounding soft tissue, the presence of deformity, limb length discrepancy, as well as the experience of the surgeon [7, 12, 13, 16, 19, 20, 24].

Table 2: Evaluation of the results [8].

| Parameter                        | Satisfactory       | Unsatisfactory                |
|----------------------------------|--------------------|--------------------------------|
| Bony union                       | United             | Not united                    |
| Residual deformity               | <5°                | >5°                            |
| Residual leg length discrepancy  | <2.5 cm            | >2.5 cm                       |
| Recurrent infection              | No more infection  | Bone and/or soft tissue infection |
| Soft tissue healing              | No exposed bone    | Soft-tissue defect remaining  |
| Permanent joint contracture      | <5°                | >5°                            |
| Persistent pain                  | No or mild pain    | Moderate or Incapacitating pain |
| Return to previous work          | Yes                | Has to change job             |
| Patient's satisfaction           | Satisfied          | Not satisfied                  |

Figure 9: Application of acute limb shortening and re-lengthening to bridge a combined bone and soft tissue defect. a) and b) radiograph and clinical photo of actively infected non union of the tibia with retained hardware, skin sinus and unhealthy skin. c) and d) intraoperative photos show complete excision of unhealthy tissues and removal of hardware through a Z-shaped incision where the horizontal limb was converted into elliptical shape to include unhealthy skin. e) acute limb shortening to close the skin and bone defects acutely. f) postoperative radiograph shows good bone contact at the docking site and proximal metaphyseal lengthening osteotomy. g) and h) clinical photo and radiograph at follow up show good limb alignment, bone consolidation and equal leg length. No bone or skin grafts were needed in this case.
Table 3: Summary of results.

|                                        | N    | %    |
|----------------------------------------|------|------|
| Total number of study cases            | 150  | 100% |
| Age                                    | 12–64 years | Average 36 years |
| Gender                                 | Males 122 | 81% |
|                                        | Females 28 | 19% |
| Previous surgery                       | 27 cases | 18% |
|                                        | (1–5 operations) | Average 2.1/case |
| Active infection                       | 109 cases | 72.6% |
|                                        | 34 With retained hardware | 22.6% |
|                                        | 45 infected open fracture | 30% |
|                                        | 30 infected nonunion | 20% |
| Organism of infection in culture       | Staphylococcus aureus (51 cases) | 46.8% |
|                                        | No growth (37 cases) | 34% |
|                                        | Pseudomonas aeruginosa (16 cases) | 14.7% |
|                                        | MRSA (5 cases) | 4.5% |
| Autogenous ICBG                        | 42 cases | 28% |
| STSG                                   | 6 cases | 4 % |
| Revision of docking site               | 114 cases | 76% |
| Limb lengthening                       | 4–11 cm. | Average 6 cm |
| Residual LLD > 2.5 cm                  | 9 cases | 6% |
| Follow up                              | 24–118 months | Average 35 months |
| Satisfactory outcome                   | 141 cases | 94% |
| Unsatisfactory outcome                 | 9 cases | 6% |

MRSA = methicillin resistant staphylococcus aureus; ICBG = iliac crest bone graft; STSG = split thickness skin graft; LLD = leg length discrepancy.

Reconstruction of a segmental bone defect with the use of a vascularized fibular autograft have distinct benefits and allow simultaneous soft-tissue coverage. However, problems are relatively common, including infection and stress fracture, and can occur at both donor and recipient sites. The technique also requires specialized microsurgical expertise [12].

An alternative approach to the problem is the induced membrane (Masquelet) technique. Union rates of between 80% and 100% have been reported [13, 15]. Other studies have reported mixed results with this technique and significant complications, including infection, amputation, fracture and risk of graft donor site morbidity [15].

The concept of allowing free open drainage of infected open fractures is not new, and it has stood the test of time [25]. Similarly, Bone transport and distraction histogenesis allow free drainage of infected nonunion after thorough debridement. In contrary to other approaches the wound may be packed open and gradually closed by means of compression – distraction. Several advantages are expected with this technique including high rate of infection clearance, bone and soft tissue reconstruction without free or local tissue grafts, deformity correction and limb length equalization [25, 26].

The widespread use of external skeletal fixation based on Ilizarov techniques has revealed several difficulties pertinent to the technique due to patient’s inconvenience with the device [6, 7, 14–16]. On the other hand, the process of bone transport and docking of bone ends could be hindered by fibrous tissue obstruction, skin invagination, segment deviation, and premature consolidation of the osteotomy [6, 8]. As a prerequisite for treatment, it is essential to recognize and define the existing complications of the open tibial fractures, and consequently the management would be successfully planned. The interference should be planned based on the requirements of the case to avoid over- or under-treatment [7]. Such complex management would not be suitable in the presence of certain factors related to the patient’s health, e.g., morbid obesity and chronic illness. The technique of ASRL has been proved to be effective in converting a complex limb reconstruction into a simpler procedure and obviates the problems related to bone transport. However, it should be avoided in the presence of soft tissue fibrosis or multiple longitudinal scars to avoid acute ischemia. Cigarette smoking has been shown to adversely affect bone healing, and the patient should quit smoking before embarking on this procedure.
Moreover, any general debilitating disease condition should be corrected to optimize the environment for this complex procedure [7, 8].

The keys to adequate debridement of infected nonunion and local tissue transfer are: 1) oncological debridement, to ensure eradication of infection, 2) square osteotomy of bone ends, for better bone contact and healing, and 3) soft tissue curtain, to avoid desiccation and infection of exposed bone ends (Figure 1). “Onco- logical debridement” has been used in preference to “radical debridement” for several reasons. It has been emphasized that surgery remains the mainstay of treatment when a curative treatment strategy is selected. A potentially curative surgery should ideally involve a wide resection of the infected tissues with a safety margin (at least 5 mm.) to ensure eradication of infection [18–21].

Bone transport (local tissue transport) is not without difficulties or complications. The most frequently encountered difficulties are: pin tract infection specially during the distraction – compression phase, skin invagination at the docking site, and patient intolerance to the procedure. However, these problems are manageable and should not influence the final treatment-outcome. A great deal of experience of the treating surgeon and hospital team is mandatory to get over these difficulties.

This study provides a clinical evidence on the ability of bone transport to comprehensively solve the problem of composite tissue loss in different case scenarios without the need for sophisticated tissue transfer procedures. The limitations of this study are its retrospective nature and lack of control group to compare the outcomes.

Based on our observations in this series, BT was defined as “Bone transport is an advancement of a local vascularized, osteomyocutaneous flap to bridge bone and soft tissue defect either gradual or acute by means of distraction histogenesis.” When conceived as an osteomyocutaneous flap, bone transport extends the umbrella of limb reconstruction to include cases where other procedures could not be safely employed. Bone transport is a powerful tool in the armamentarium of Orthoplastic limb reconstruction.

Ethics and Consent

- Ethical approval: All procedures performed in this study were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.
- Informed consent: Informed consent was obtained from all individual participants included in the study.

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Competing Interests

The authors have no competing interests to declare.

Author Contributions

- Mahmoud El-Rosasy: Conception and design of the work, performed surgery and drafting the article.
- Ashraf Mahmoud: Performed Surgery, data analysis and interpretation and wrote manuscript.
- Osama El-Gebaly: Performed surgery, data collection and review manuscript.
- Edgardo Rodriguez-Collazo: Critical revision of the article and final approval for submission.
- Alessandro Thione: Critical revision of the article and final approval for submission.

Guarantor

Prof. Mahmoud El-Rosasy, MD is the guarantor.

Peer Review

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