Current trends in craniofacial distraction: A literature review

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Abstract

The techniques and procedures involved in craniofacial distraction are constantly evolving. The understanding of histological and biochemical response at the distraction site is now improved. The cascade of events in distraction osteogenesis (DO) differs significantly from the typical fracture healing, and a better knowledge about these events has helped us identify suitable candidates for DO, make appropriate modifications to the distraction protocols and minimize the risk of complications. Recent advances in the manufacturing techniques have also facilitated the availability of distractors of various shapes and designs, which are now changing the way different craniofacial defects are being treated. Small but rigid intraoral distractors now enable easy placement, are well tolerated by patients and allow for a long consolidation period. The introduction of newer approaches toward treatment, together with the simultaneous management of different craniofacial defects at multiple osteotomy sites and enhanced surgical accuracy with the help of digital imaging, have made treatment outcomes more predictable.

Key words: distraction, repair, Ilizarov technique, craniofacial syndrome, computer-assisted three dimensional imaging

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Introduction

Distraction osteogenesis (DO) is a well-established technique in the field of orthopedics, as it has been used for several decades for limb lengthening and the repair of long-bone defects. The standard protocol of DO is based on careful planning, with special attention being paid to the anatomy and blood supply of the osteotomy site, the patient's general health, and the design and mechanical properties of the distractor device.

The procedure is commenced with an osteotomy, followed by the insertion of a distractor. The osteotomy site is allowed to mature for a few days (the latency period); then, the distraction phase begins. The distractor is opened at a specific rate and rhythm so that the proximal and distal fragments of the bone start separating, leading to the mechanical induction of new bone formation between the bony surfaces at the osteotomy site.¹ Once the desired lengthening of the bone is achieved, the process of distraction is stopped and the newly formed non-mineralized bone (callus) is allowed to mature for a period of several weeks to several months as part of the consolidation phase (Fig. 1).¹

Fig. 1. Phases of distraction osteogenesis (DO)

Insights into the biological basis of craniofacial distraction

Histologically, the latency phase of DO closely resembles typical fracture healing, which involves hematoma formation, local inflammatory response and the influx of mesenchymal stem cells.^{2,3} During rapid bone formation in the latency period, endochondral bone formation is observed along the periosteum. The region in the middle of the healing callus, regarded as a fibrous interzone (FIZ), is rich in fibroblasts, chondrocytes, and cells that have the morphological features of both chondroblasts and fibroblasts.^{4,5} The process of ossification starts from the area adjacent to the bone and FIZ ossifies the last.^{5,6}

The predominant mechanism of bone formation is intramembranous, characterized by the formation of type-I collagen; however, a zone of endochondral bone formation is frequently observed.⁷⁻⁹ This process differs from the typical endochondral bone formation, as there is no capillary ingrowth in this cartilaginous matrix and the formation of type-II collagen by these chondroblast-like cells switches over to the production of type-I collagen. This process has been named as 'transchondroid bone formation'.¹⁰

The molecular expression during DO shows certain differences when compared to the molecular expression during fracture healing. Interleukin-6 (IL-6) concentration is increased not only during the initial inflammatory phase, but also when the distraction phase is started. Cho et al. showed that IL-6 could significantly enhance intramembranous ossification and had an overall anabolic effect during DO, contrary to its catabolic effect during fracture healing.¹¹ The members of the transforming growth factor beta (TGF- β) superfamily are other important mediators associated with DO, the expression of which is greater at the distracted osteotomy sites as compared to the non-distracted osteotomy or fracture sites. The expression of TGF- β is positively correlated with the rate of distraction, which promotes new bone formation through osteoblastic proliferation.^{2,12} A similar pattern of expression has been described for bone morphogenic protein (BMP)-2 and BMP-4.^{13,14} In the absence of mechanical strain, they gradually disappear from the distraction site. Moreover, the addition of BMP-2 has been shown to reduce the latency period, and thus may be used to reduce the overall treatment time.¹⁵ Other important growth factors that play a role during different phases of DO include insulin-like growth factor-1 (IGF-1) and fibroblast growth factor (FGF)-2.¹⁶

Angiogenesis is an essential part of DO, in the absence of which non-bony union occurs. Angiogenesis during DO is more intense as compared to that during fracture healing, with studies reporting about a ten-fold increase in the blood flow during the distraction phase as compared to the normal blood flow.⁵ Similarly, since maximum bone formation occurs during the consolidation period, the maximum increase in the vessel volume has also been found during this period. The experimental inhibition of vascular endothelial growth factor (VEGF)-mediated angiogenesis also results in reduced osteogenesis activity.¹⁷ Although new vessel formation begins during activation, the maximum increase in the vessel volume occurs during consolidation, suggesting a link between angiogenesis and bone formation.¹⁷⁻¹⁹

Evolution of distractor designs and techniques

The evolution of distractor devices goes along with the evolution in the DO techniques. The concept of intra-oral and extraoral distractor devices goes back to the era

of McCarthy, when he used unidirectional extraoral distractors to lengthen the mandibles of patients suffering from congenital mandibular deficiencies in 1989.^{20,21} The following year, Guerrero reported the use of an intraoral tooth-borne distractor for mandibular symphyseal distraction.²²

Evolution of distractors for maxillomandibular distraction

Generally, mandibular distractors can be categorized into extraoral and intraoral ones, intraoral distractors being tooth-borne, bone-borne or hybrid. On the other hand, extraoral distractors are always bone-borne (Fig. 2). These distractors allow vector adjustment during distraction. However, the 2 major drawbacks of these distraction devices were the uniplanar control of the vector and extraoral placement. A common type of extraoral distractor is a two-pin distractor, which offers the advantage of easy placement in situations where minimal bone mass is available, without compromising the quality of callus formation and bone healing. Soon after the introduction of unidirectional distractors, it was realized that most of the defects were three-dimensional (3D) and linear distractors failed to completely restore them. When distractors were applied to different parts of the ramus, angle and body of the mandible, the results were rarely ideal and never precise enough to achieve optimal dental occlusion. In 1995, Molina and Ortiz Monasterio²³ demonstrated the use of bidirectional distractors by creating 2 osteotomy sites in the affected mandibles (Fig. 3), which further led to the development of multidirectional distraction devices, such as the ACE/Normed multidimensional distractor and the multi-vector mandibular distractor of McCarthy.²⁴

Fig. 2. Rigid external distractor

Another major leap in the evolution of distractors was the introduction of intraoral distractors, which were less conspicuous, easy to tolerate, socially acceptable, and free of the risk of facial scars. The realization of intraoral distractors was possible due to a significant reduction in the size of distractors

Fig. 3. Bidirectional distractor

and alteration in the distraction design. They were initially stock made, which meant they could be used for a specific bony location in any patient, as reported by Diner et al.,²⁵ or were universal in nature and could be placed on any site at the discretion of the surgeon, like the Dynaform Intraoral Distractor.²⁶ A newer category of distractors were custom made and designed according to the needs of a specific patient. Razdolsky's tooth-borne and hybrid ROD devices are examples of distractors that allow the preprogrammed fabrication of the device along the predetermined axis of distraction according to the needs of the patient.^{27,28}

The need for multidirectional or curvilinear distraction is often appreciated by oral and maxillofacial surgeons and orthodontists (Fig. 4). Multidirectional distractors are often large in size and need to be placed extraorally. A curvilinear distractor was described by Seldin²⁹ in 1999 on animal models (Fig. 5). The curved design allows for the simultaneous lengthening of the mandibular body and ramus along a curved path, which is very similar to the pattern of natural growth of the mandible.^{30–32} In addition, this pattern of mandibular lengthening is favorable for the correction of an anterior open bite, a common iatrogenic condition during mandibular distraction.³³

Fig. 4. Multidirectional distractor

Fig. 5. Curvilinear distractor

A general concept that DO allows greater mid-facial advancement than the conventional orthognathic surgeries has been verified by a retrospective single-center study.³⁴ Bone healing in the maxilla is relatively faster. Studies have shown that the traditional consolidation phase duration of 8 weeks or longer can be shortened without compromising stability.^{35,36} Though these devices have served the specialty well, there is still a need to develop an appliance system that would carry out automated and continuous distraction. It is not uncommon to find that many patients could not adhere to the distraction protocol – intentionally, due to the pain or discomfort associated with activation, or unintentionally, when they failed to comprehend or remember the distraction protocol. Recently, newer devices with hydraulic, motor-driven or spring-mediated mechanisms are being developed. The first reports on animal models are satisfactory, but significant improvement in the device design is needed, along with the need to include a distraction protocol that is compatible with human body, before these devices could be used for routine patient care.^{37,38} Despite these deficiencies, it is expected that soon these appliances will become common, and thus will simplify the distraction process for patients and parents.

Evolution of distractors for cranial and craniofacial defects

In patients with differential dysmorphology involving the axial and sagittal planes, the en bloc movement using Le Fort III osteotomy may treat the position, but the axial dimension may remain untreated. The bipartition monobloc advancement using vertical osteotomy in the midline to pull the central face gives effective correction in midface concavity.³⁶ Greater soft-tissue resistance laterally as compared to the center of the face during advancement results in a more convex shape of the sagittal facial profile. The separation of the zygoma after Le Fort III osteotomy at the zygomaticomaxillary suture also

aids in differential advancement and the repositioning of the midface in the desired position relative to the corneal surface.

In patients with a shortened skull, DO allows correction over large distances, with the gradual movement and changes of the soft-tissue matrix. The contemporary distraction technique allows for the distraction of the cranium and skull base. The expansion of the anterior cranial fossa could also be performed, either in isolation or with the subcranial movement using the monobloc procedure, with the latter technique allowing for the simultaneous advancement of the inferior orbital rim, an increase in the dimension of the nasopharynx and overjet correction. The monobloc craniofacial advancement of the midface along with the anterior cranial vault is usually carried out at the age of 7–9 years, when the growth of the midface is almost complete.³⁹ However, this procedure may involve a significant risk, as the sinus–brain barrier in the anterior cranial vault can be violated. This has resulted in a reduction in the frequency of using this procedure, which is usually limited to cases with circumorbital symmetric retrusion, in which the conventional staged advancement of the midface and the anterior cranial vault is not possible.^{40,41} Contrary to this approach, gradual expansion and advancement with DO minimizes the risk of the creation of dead space, and the subsequent morbidity associated with it.⁴² Though some authors have advocated the use of frontofacial monobloc distraction at the age of 1 year, the long-term results as well as the final esthetic and functional outcomes are yet to be investigated.⁴³ In this regard, the use of early monobloc distraction is usually limited to life-threatening dysostosis, e.g., Pfeiffer type-II deformity.⁴⁴

Stimulation of bone repair

To minimize the duration of bone repair during DO, various surgical and non-surgical strategies have been implemented. Non-surgical strategies include electric and electromagnetic stimulation, injecting growth hormones, cytokines and BMPs, and the use of low-level laser therapy (LLLT) and low-intensity pulse ultrasound (LIPUS).

The acceleration of bone repair and the modification of the period of inflammation with biological stimulation can be achieved by means of lasers.^{45–48} Low-level laser therapy was used in the past for the treatment of unhealed ulcers.⁴⁹ It promotes osteoblastic activity during bone repair, which enhances the rate of bone healing.⁵⁰ The factors affecting the laser dose may result in variations in the effectiveness of LLLT. These include power output and the duration of the applied therapy. The doses recommended by various studies vary from 10–112.5 J/cm²^{51–53} to 0.03–3 J/cm².^{54–56} Another important criterion that affects the effectiveness of the therapy is the type of the target tissue, as this may result in variations in the depth

of penetration. Mucosa is more susceptible to penetration as compared to fat and muscle tissues. Depending on the dose, the therapy may cause biostimulation or bioinhibition.^{57,58} Therefore, low doses (3–5 J/cm²) are recommended rather than high doses (50–100 J/cm²) to prevent the destructive effect.⁵⁹

Ultrasound therapy produces micromechanical vibrations similar to physiological stress. The piezoelectric and angiogenic effects of ultrasound on bone apparently produce the therapeutic effect the therapy.⁶⁰ The application of ultrasound has been reported in mandibular fractures in rabbits.⁶¹ Harris treated mandibular osteoradionecrosis with ultrasound in humans.⁶² An increased healing ratio of 88% has been reported when using ultrasound with the conventional therapy in 1,317 fracture cases in human subjects.⁶³ With the application of LIPUS for 20 min/day, following DO for 10 days to lengthen the right tibia of rabbits, improved bone mineral density (BMD) at callus with increased stiffness and fracture strength have been observed.⁶¹ The application of 20–50 mW/cm² LIPUS results in a rise in tissue temperature <1°C. This brings about significant changes during bone formation and in the amount of enzymes.^{64,65} The tissue changes include a decrease in edema through the stimulation of mast cells.⁶⁶ Furthermore, an increase in the adhesion of leukocytes to endothelium during the inflammation period causes the increased release of macrophages, fibroblasts and VEGF, and the stimulation of collagen synthesis from fibroblasts during the healing phase has been reported in various studies.^{67–70} Increased BMD was reported in a study conducted on dogs, which received 40 mW/cm² LIPUS for 20 min/day during the distraction phase at a 2-week interval.⁷¹

Both LLLT and LIPUS have been reported to be safe and non-invasive to improve the outcome of the DO treatment.⁷² Kocyigit et al. investigated the effects of ultrasound stimulation (LIPUS) and laser therapy (LLLT) on the BMD of the bone formed during DO with the use of dual energy X-ray absorptiometry.⁷² Both methods showed improvement in healing after DO and greater BMD in the exposed groups (LIPUS or LLLT) as compared to the controls.⁷²

To improve the process of healing during and after distraction, several novel techniques are being implemented. A recent study investigated the effect of stem cells from human exfoliated deciduous teeth (SHED) on healing after DO.⁷³ The results were quite promising, denoting significantly greater bone formation in the SHED-transplanted groups, thus improving the quality of union and the speed of bone maturation.⁷³

Scientists are trying to explore the effects of different growth factors and biochemical mediators on DO. The role of BMPs and FGFs has long been documented. Recently, the positive effects of recombinant human erythropoietin (rhEPO) and platelet-rich plasma (PRP) have also been documented.^{74,75}

Recombinant human erythropoietin has been shown to increase the number of osteoblasts and blood vessels, and reduce the number of osteoclasts, leading to a larger area of bone formation.⁷⁵

These innovations in the science of DO can have significant clinical implication in the future. These methods may help reduce the latency and consolidation periods, improve bone strength after DO, improve the vascularity of tissues, and reduce the risk of complications.

Virtual surgical simulation and three-dimensional distraction osteogenesis

The process of DO in the craniofacial region consists of both linear and rotational movements as opposed to only linear movements in the case of epiphyseal lengthening. This is because of the morphology of the structures present in the head and the neck region. The vector produced by the distraction device is based on its position in relation to the surrounding bony structures.⁷⁶

Hence, for advances the desired movement, the careful planning of the osteotomy cuts and the accurate placement of the device are fundamental. Innovations in 3D imaging techniques in the current era have enabled the accurate visualization of the craniofacial structures in all 3 planes of space.⁷⁷

Recent advances in the virtual planning software have overcome some limitations, including achieving the desirable occlusal, functional and esthetic outcomes of two-dimensional (2D)-based DO. Intraoral distractors can produce movement only in a single direction; the accurate vector is dependent on the position of the device. Furthermore, intraoral devices are indicated for smaller defects, which make their placement more challenging due to a limited working field. The accurate placement and positioning of the device becomes even more important with intraoral distractors.⁷⁸

Hence, the accurate transfer of the surgical procedure planned with the aid of 3D software is mandatory for achieving the desired results. Another advantage of the virtual planning software is that multiple treatment simulations can be performed to determine the most feasible plan in terms of risks, benefits and cost, which can be set for a specific patient. The surrounding structures, including the developing tooth germs, may be taken into consideration when planning the osteotomy cuts. With the introduction of rapid prototyping machines and 3D printers, the desired surgical stent and distractor templates can be computer-aided design/computer-aided manufacturing (CAD-CAM)-fabricated to further increase the accuracy of the planned surgical procedure.^{79,80} Lastly, distractors may be modified to adapt to the bony segments on models to reduce the intraoperative surgical time and inconvenience.

The following are the basic guidelines for 3D-based DO and the fabrication of the surgical stent (Fig. 6):

- data acquisition: 3D imaging techniques, such as cone-beam computed tomography (CBCT), computed tomography (CT), magnetic resonance imaging (MRI), etc., have been used for data acquisition; these, along with the virtual models, are correlated on a common Cartesian system to construct a 3D model;
- data analysis and the determination of skeletal discrepancy: the exact skeletal discrepancy in all planes is computed using the 3D model; based on this, the exact amount and direction of movement of the bony segment is determined;
- determination of the position and angulation of the distractor: the vector is one of the significant factors for the achievement of the planned movement; this vector is determined by the position and angulation of the device on the bony segment, and the type of distractor used. With a unilateral distractor, the position and angulation becomes even more significant, as the distractor can be moved only in 1 plane. Various mathematical formulae can be used to calculate the required length and angle with respect to the bony bases by measuring the angle between the horizontal and vertical vectors^{81,82};
- treatment simulation: the osteotomy cuts are planned according the vector direction, taking into consideration the surrounding soft and hard structures. Usually, the osteotomy line is perpendicular to the vector distraction. The osteotomy cuts are simulated and the device is placed on the virtual models. If the movement is not satisfactory, an alternative plan may be simulated. An advantage of the virtual treatment planning software is the possibility of altering the position and angulation of the device until the desired result is achieved;

- model surgery and the fabrication of the surgical stent: various types of rapid prototyping, such as stereolithography and fused deposition modeling, may be used to fabricate models.^{83,84} The planned surgery is then performed on these models and a template distractor can be adapted to assess the feasibility of the treatment plan. Impressions of both the device and the bony surface are taken for the fabrication of the surgical stent. This stent is then used to transfer the planned surgery to the operating room.

Discussion

Recent advances have profoundly extended the scope of craniofacial DO. The incorporation of new diagnostic and treatment planning tools have improved the predictability of outcomes, providing the possibilities of using DO not only for deformity correction, but also in other situations.⁷⁷ Osteodistraction may help the orthodontist to treat crowded dental arches with non-extraction therapy by improving the arch length and perimeter in severely crowded cases.²² Also, the regeneration of the alveolar bone for the placement of implants in patients with atrophic bone may be possible with this technique, which would be preferable to tissue reaction and rejection, as in the case of artificial bone used for the augmentation purpose. In the cases of ankylosis and discrepancy in vertical height, treatment with distraction may also help the tooth attain an esthetic and functional position.

The application of the concept of acceleration in the healing process has also helped in reducing the duration of the consolidation period, offering a great advantage to the clinician and patients,^{51,60} and distraction histogenesis occurring during DO allows for larger skeletal corrections with a lower risk of relapse due to soft tissue adaptation. Moreover, advances in the designs of distractors have improved the efficiency of treatment in achieving functional and esthetic results.

Conclusions

Distraction techniques have established themselves as a highly efficient and practical mode of treating craniofacial defects. Newer techniques are making distraction a routine procedure with a long-term follow-up now available in the published literature. Orthodontists need to keep themselves updated to the latest advances in the field of craniofacial distraction to be able to offer the most suitable treatment to their patients.

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Fig. 6. Guidelines for three-dimensional (3D)-based DO

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