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Distraction Osteogenesis of the Maxillofacial Skeleton: Biomechanics and Clinical Implications

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Abstract

Distraction osteogenesis (DO), also called callus distraction, callotasis, osteodistraction, and distraction histogenesis is a biological process of regenerating neo formed bone and adjacent soft tissue by gradual and controlled traction of the surgically separated bone segments. Physical and biological parameters affecting the success of DO include the macro and microscopical bone anatomy, the direction and amount of the applied distraction forces, and the regenerative capacity of the tissues involved. Force transduction via adjacent structures (joints, ligaments, muscles, and soft tissue) influences the regeneration of the tissue between the bone fragments by modulating the stress produced within the callus. The clinical applicability of DO is dependent upon device-related and tissue-related factors. Device-related factors affect the mechanical integrity of the distractor and the stability of bone fixation. The number, length, and diameter of fixation pins, the rigidity of the distractor fixation, and the material properties of the device affect the clinical result of the distraction procedure, additionally, the orientation of the distraction device and the resulting distraction vector relative to the anatomical axis of the distracted bone segments. In case of the jaws – the occlusal plane and the joint position are important considerations. Tissue-related factors affecting the quality of the generated distraction tissue include cross-sectional area, the density of the distracted bone segments, the length of the distraction gap, and the tension of the soft tissue envelope. In the maxillofacial skeleton, DO replacing many of the traditional surgical treatment for Congenital and acquired deformities. Here, the Biomechanics of DO and its Clinical Implications in the maxillofacial skeleton will be discussing.

Keywords: Distraction osteogenesis; Biomechanics; Clinical implications

Introduction

Distraction Osteogenesis (DO), also called callus distraction, callotasis, osteodistraction, and distraction histogenesis is a biological process of regenerating neo formed bone and adjacent soft tissue by gradual and controlled traction of the surgically separated bone segments [1]. The history of DO begins with the old techniques of repositioning and stabilization of bone fractures used by Hippocrates [2]. It was first described in the field of orthopaedics by Codivilla [3] in 1905 who published a case report of bone elongation techniques for femoral extension using axial forcesof distraction (Figure 1). Nevertheless, this technique gained its popularity after its development by the extensive work of Illizarov [4,5]. The Russian surgeon developed innovative devices for skeletal fixation and osteotomy techniques that deliver minimum trauma to the periosteum and to the bone marrow (Figure 2). His landmark set of clinical experiments led to the discovery of the biologic basis of osteo distraction, the Ilizarov effects, which suggest that gradual traction applied on living tissues can stimulate and maintain regeneration and active growth, and that the mass and shape of bones and articulations depend on their blood supply and on their functional burden [4-7]. His studies later determined the technical protocols for DO, and are still used as a basic reference for studies in this field. Following the success of DO in the orthopaedic field, the application of DO in the maxillofacial complex began in 1973 when Snyder et al. [8] used a Swanson external fixator to lengthen a canine mandible. In this experiment, he surgically shortened one side of the mandible by removing a 1.5 cm segment and then allowed the bone to heal. This created a large cross bite that was surgically corrected 10 weeks later by attaching an external fixator, performing an osteotomy, and slowly expanding the device until the cross bite was normalized.

McCarthy [9] performed the first human mandibular distraction in 1992, using an external distractor in patients with hemifacial microsomia. This study was a landmark clinically in that it proved for the first time that mandibular distraction could be successfully performed in humans without significant risk of infection or complications. That report ushered in the modern era of clinical maxillofacial distraction.

Since that time, successful distraction of various component of the maxillofacial skeleton has been performed on a multitude of patients, and the technique has become an accepted method of treatment worldwide. The patient population eligible for distraction now includes those

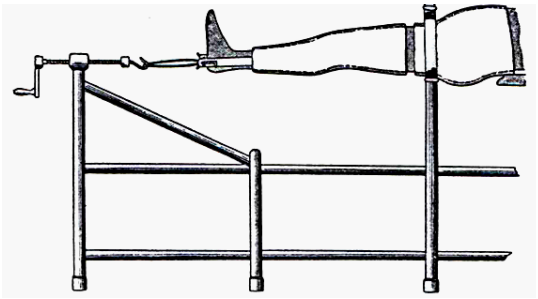

Figure 1: A diagram which show the whole apparatus at work, while the traction and the counter-traction are applied to the two portions of the plaster apparatus.

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with a variety of maxillofacial deficiencies, maxillofacial microsomia, micrognathia, temporomandibular joint ankylosis, posttraumatic growth disturbances, post-oncologic ablation, midface hypoplasia, maxillary deficiency, zygomatic deficiency craniosynostosis, Cleft Lip and Palate (CLP), and Transverse Discrepancies [10,11].

Biological Aspects

At histologic level, the healing process in DO differs from that of a fracture's repair in 2 basic aspects: 1) ithas the advantage of having a controlled microtrauma; and 2) the ossification mechanism is membranous, not endochondral [12]. In the first histologic study in a dog mandibular elongation model has been performed, with evaluation at days 10 and 20 of the distraction phase, and days 14, 28 and 56 of the consolidation phase. They observed 4 distinct areas and stages: from within the gap to the edges of the initial bone, a central area of fibrous tissue with collagen fibres parallel to the distraction vector, with spindle-shaped fibroblast-like cells and mesenchymal stem cells; a bone formation area in the fibrous tissue, with the formation of bone spicules coated with osteoblasts; a bone remodelling area, with the advance of resorption and apposition fields; and an area of mature bone with formation of cortical bone [12].

In the distraction process, there are 3 fundamental sequential phases in which different biologic phenomena are produced. These have been experimentally studied in bones of endochondral or intramembranous origin [1,4,5] (Figure 3).

Distraction Phases

Latency phase

Latency phase is the period between performance of osteotomy and start of the distraction, during which soft callus is formed. Time periods usually applied range from 0 to 7 days and coincide with the initial events in the normal process of bone repair. In most cases, the osteotomy creates an initial defect of approximately 1.0 mm. The basic principles of using new fresh burrs, using constant irrigation during the drilling process, and minimizing thermal injury to the bone must be strictly followed in this technique. Furthermore, the actual placement of the pins and/or screws should be meticulous. If a pin or screw needs to be backed out, it is often better to drill a new hole and place the pin/screw with a fresh placement than to risk unstable and inadequate fixation that will loosen and lead to failure of the distraction process. Histologically, the initial clotting is converted at 3 days into granulation tissue (inflammatory cells and fibroblasts), which becomes increasingly fibrous due to the presence of collagen and increasingly vascular through the appearance of new capillaries. At this stage, recruitment of mesenchymal stem cells from the bone medulla and adjacent periosteum begins [13].

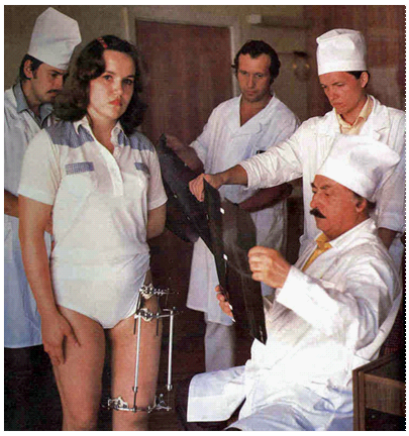

Figure 2: Percutaneous manual osteoclasis by Gavriil Ilizarov.

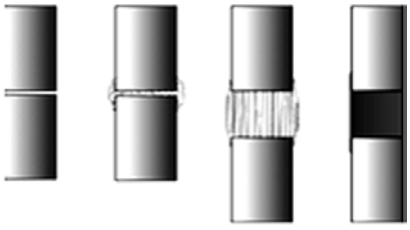

Figure 3: Distraction phases: A) Osteotomy, B) Latency period, C) Distraction period, D) Consolidation period.

Distraction phase

The period in which traction is applied to the transport bone fragment and the formation of new immature woven and parallel-fibered bone commences. This phase usually lasts 1-2 weeks, and the traction modifies the normal development of the regeneration process. During this phase, the distraction device is activated by turning some type of axial screw, usually at 1 mm/day in four equal increments of 0.25 mm each (Chart 1).

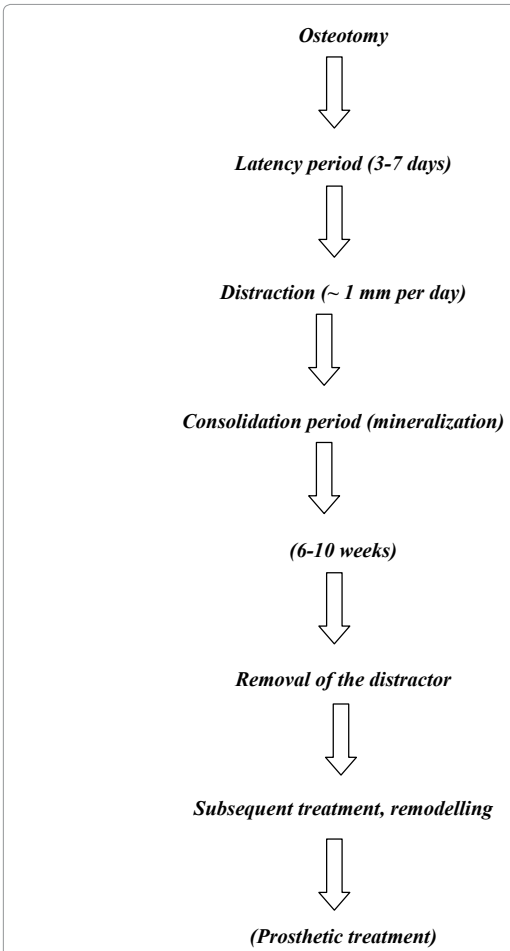

Chart 1: Timetable of a distraction.

A dynamic microenvironment is created, with formation of tissue parallel to the distraction vector. There is an increase and prolongation of angiogenesis and an increase proliferation of spindle-shaped fibroblast-like cells. This type of spindle shaped cell is situated peripherally and throughout the vessels, producing more collagen parallel to the distraction vector. These cells are ultra-structurally characterized by increased endoplasmic reticulum in the cytoplasm and increased nucleoli in the nucleus [13].

The collagen is mostly type I, which, alongside the angiogenic increase, would support the theory that tension favours intramembranous but not endochondral ossification [14]. It has also been observed that these cells can express osteocalcin, osteopontin, and alkaline phosphate, evidence of some osteoblastic differentiation. It has been demonstrated that the application of tension favours the trans-differentiation of chondroblasts and fibroblasts into osteoblasts. Thus, tension causes chondroblasts to express type I instead of type II collagen [15].

The increase in vascular growth is 10-fold that in normal repair, increasing the supply to the fibrous area of mesenchymal stems cells, which differentiate into chondroblasts (more evident in long bones) and osteoblasts. The osteoblasts present arise in the number and size of mitochondria, and an increase in cisterns of the endoplasmic reticulum with more ribosomes. Daily distraction aligns the collagen fibres in parallel bundles that channel the growing vessels and perivascular cells into longitudinal compartments. Histo-chemical study of this phase by Illizarov [4,5] also showed an increase alkaline phosphate, pyruvic acid, and lactic acid (products of enzymatic metabolism). It appears that the moderate and controlled tension exerted by the distractor on the granulation tissue produces a greater differentiation of mesenchymal stem cells into osteoblasts and also favours a higher production of bone proteins by osteoblasts [13].

The bone fragment to be distracted and the soft callus of the gap must be immobilized during the distraction and consolidation phases. Movement in the area would interrupt the microcirculation by which pluripotential cells differentiate into chondroblasts, which require less oxygenation in their formation. It is also mandatory to facilitate a continuous blood supply by a careful surgical handling of the periosteum (or endosteum in long bone distraction) [4,5].

Mofid et al. [16] experimentally modified the protocol established by Ilizarov, based on the improved regeneration produced by compression in fracture callus. In a rabbit mandibular elongation model, they applied tension and compression (1 mm/day) on alternate days for 3 weeks. After the distraction phase, the dynamic histomorphometic study showed a higher mineral apposition index in the distraction-compression group versus a distraction-only group (3.2 μm/day vs 2.1 μm/day). At 5 weeks of consolidation, the thickness of cortical areas was also significantly greater in the distraction-compression group than in the distraction group (83% vs. 49%).

Consolidation phase

Consolidation phase is the period that allows the maturation and corticalization of the regenerated bone. Typically, the consolidation phase is twice as long as the time required for activation. In craniofacial bones, a 3-5 week phase is recommended for children and a 6-12 week phase for adults, although the appearance of bone with identical characteristics to those of the initial bone may take more than a year. Once the distraction is ended, the central fibrous and osteoid areas ossify and gradually mineralize in a largely intramembranous manner in facial bones, becoming immature bone that will form remodelling areas for transformation into mature lamella bone. In maxillary bones, the ossification is largely intramembranous, although foci of endochondral ossification have been reported by some authors. Such foci may result from the instability of the bone fragments or from a high distraction rate and don't interfere with the final regeneration, although this phenomenon has yet to be elucidated [17].

Molecular mechanisms

Understanding the molecular events that concur to osteogenesis during successful DO has important clinical implications, as it is a step toward the development of therapeutic interventions for accelerating regeneration and abbreviating consolidation time. In our view of the molecular biology of osteodistraction, Bouletreau et al. [18] has shown that a number of growth factors, cytokines, and extracellular matrix (ECM) proteins are involved in the processes of synthesis, mineralization, and maturation of bone tissue at the distraction gap. mRNA and protein expressions of these regulatory factors fluctuate along the different stages of distraction, and applying the proper protein at the right time should optimize the outcome. Okazaki et al. [19] reported on the use of recombinant human Fibroblast Growth Factor (FGF) at the end of the distraction period. It was observed that bone levels of insulin-like growth factor 1 increased immediately after the distraction compared with levels in normal bone. However, serum insulin-like growth factor 1 levels began to increase at the start of the distraction, leading to speculation that the bone accumulation is due to deposition of a systemic rather than local increment [20].

In vitro, 24 hours of continuous cyclic mechanical stretch has led to increased mRNA levels of transforming growth factor β-1, IGF-1, and FGF [15]. Interleukin-6, a cytokine believed to stimulate osteoclastic resorption, was also increased in the 24 hour cycle period, which may substantiate the "coupling phenomenon" between bone formation and resorption [21] and may reflect an increase in the absolute number of osteoblasts. The different stages of bone maturation also feature a transition on the dominant type of collagen, varying from type III just after the fracture [22] to type I in the late phases of bone maturation [23]. Non collagenous ECM proteins such as osteocalcin were proven torelate temporally and spatially with successful DO, and vascular endothelial growth factor expression is increased after the fracture and throughout the distraction, as angiogenesis is of paramount importance for bone healing (Figure 4) [24].

Not only chemical factors but also physical factors affect the outcomes of osteodistraction. Different studies evaluated the effect of electric and ultrasound stimulations on DO and concluded that the possibility of enhancing osteogenesis and improving bone quality using electric and ultrasound stimulations [25-27].

Several factors [28] influence the physiologic process of DO, and these can be separated into 2 basic groups: bone healing factors and distraction factors (Table 1).

Factors that affect bone healing can be local or systemic in nature. Viability of osteocytes and osteoblasts is essential to provide an adequate source of osteogenic activity at the distraction site. Hence, careful surgical technique should be used to minimize thermal or mechanical injury to the periosteum and endosteum, which are the main sources of osteoblast precursors. Similarly, an adequate blood supply to the distraction site is critical to osteogenesis. Arterial insufficiency may lead to ischemic fibrogenesis within the regenerate, yielding a loose, irregular collagen network instead of the desirable

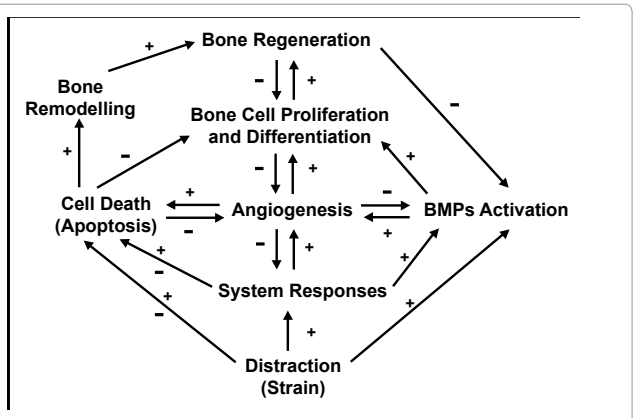

Figure 4: The diagram summarizes the regulatory and feedback cycles of biologic cascades involved in distraction osteogenesis. All factors in the diagram are interdependent and have positive (+) or negative (-) feedback cycle and effect on each other (Gang li 2004).

Local Bone-Healing Factors	Systemic Bone-Healing Factors	Distraction Factors
Osteoprogenitor supply	Age	Rate of distraction
Blood supply	Metabolic disorders	Frequency of distraction
Infection	Vitamin D deficiency	Latency period
Soft tissue scarring	Connective tissue disease	Rigidity of fixation
Bone stock	Steroid therapy	Adequate consolidation-period
Prior radiation therapy	Calcium deficiency	Length of regenerate

Table 1: Factors that affect physiologic process of DO.

dense, regular collagen pattern. Venous outflow obstruction has been associated with cystic degeneration of the regenerate. The clinician, therefore, needs to ensure that the soft tissues that surround the site of the proposed distraction are well vascularized. Early studies in long bones concluded that both an intact periosteum and endosteum were critical to successful osteogenesis; therefore, many advocated that a corticotomy be performed only through a minimal periosteal opening. More recently, however, investigators have demonstrated that the periosteum alone can provide sufficient osteogenic capacity for a healthy regenerate and this is especially true in the well-vascularized membranous bone of the craniofacial skeleton. Prior radiation therapy to the distraction site has been shown to not adversely influence the results of distraction in the canine model, and when using DO to repair segmental defects, the status of the surrounding soft tissues will likely be the key factor that influences outcome [29].

Biomechanical aspects

The biomechanical impact of distraction osteogenesis on regenerating bone tissue is a highly complex and dynamic process. Physical and biological parameters affecting the success of distraction osteogenesis include macro extrinsic factors and microscopical intrinsic factors. Macroscopic extrinsic factors, such as distractor design (number, diameter, and length of distraction and retention screws, and distractor material), direction and amount of the distraction vector and the loading of the distracted area; and microscopic intrinsic factors or tissue biomechanical factors, such as anatomic shape and density of the distracted bone, and types and the regenerative capacity of adjacent soft tissues [1].

The distractor design influences various factors: difficulty or ease of placing or withdrawing the device after the consolidation, adequacy of the distractor anchorage to achieve stability of the bone blocks, and interference or not with the functions of the involved bone or adjacent soft tissues due to its size. The clinical application of distraction in the field of orthopaedics demonstrated the importance of the direction of the distraction. Thus, the distraction axis can be parallel to the anatomic axis of the femur but not to the biomechanical axis of the loading of the bone, which can produce different deformities in the knee when the elongation is completed. This phenomenon has been studied in mandibular elongation, observing that for 1 mm of mandibular elongation there is a lateral displacement of the distractor of 0.25 mm that clinically manifests as distortion of the distractor, resorption of the bone adjacent to the anchorage screws, or transmission of inappropriate force to the condyles. This should be avoided by the use of distractor models that can be maintained as parallel as possible to the distraction vector throughout the elongation period [30].

In alveolar distraction, the final position of the distracted tissue must favour the aesthetic and functional outcome of the prosthodontic treatment. Stable fixation of the osteotomized bone segments is a critical factor in successful distraction. Studies have demonstrated that stable fixation is associated with excellent regenerate bone formation without a cartilaginous intermediate and with complete remodelling after approximately 10 weeks of rigid external fixation. In contrast, decreased device stability has been shown to result in the formation of a cartilaginous intermediate and a significant delay in osseous remodelling [31].

The loading of the distracted area has been investigated in rats with distracted femur. In 1 group, the distraction areas supported the weight of the animal, whereas they supported no load in another group whose extremities were amputated below the knee. At 4 days of consolidation, the load-bearing group showed a greater proportion of regenerated bone and a higher expression of morphogenetic proteins 2 and 4 (BMP-2 and BMP-4), osteocalcin and type I collagen. The no-load-bearing group showed a higher expression of type II collagen. Therefore, loading also favours bone regeneration by distraction, although the most appropriate load levels have not been established [32].

Force transduction via adjacent structures (joints, ligaments, muscles, and soft tissue) influences the regeneration of the tissue between the bone fragments by modulating the stress produced within the callus. In clinical terms, gradual distraction of bones mechanically elongates the gap tissue. Because the osteoblast is the principal cell for bone growth and regeneration, straining of osteoblasts seems to be the major determinant influencing the subsequent tissue responses in distraction osteogenesis. Histomorphological and ultrastructural analyses reveal that successful DO induce osteoid and bone formation without a substantial cartilaginous intermediate tissue. Furthermore, the tensile distractions across a surgical osteotomycreates nascent bone formation in a plane parallel to the applied tension vector. This new bone forms centripetally from the osteotomized bone edges toward the centre of the distraction gap [33].

A singular aspect of the distraction technique is the fact of regeneration is followed by a simultaneous expansion of soft tissues, including blood vessels, nerves, muscles, skin, mucosa, fascia, ligaments, cartilage and periosteum. This adaption process of adjacent soft tissues provoked by tensions generated for the distraction forces is also known as distraction histogenesis. Distraction osteogenesis shares many features of embryonic growth, fetal growth, and neonatal limb development [34], as well as normal fracture gap healing [35]. However, the exact cellular and molecular mechanisms of osseous and non-osseous regeneration are still not well understood. Ample

evidence has emphasized the contribution of both periosteum and local neovascularity on bone formation during distraction [36,37].

Types of DO

According to distraction technique into two types:

Callotasis: distraction of the fracture callus.

Distraction epiphysiolysis and chondrodiatasis: Distraction of the bone growth plate.

DO can be also classified into three types: (Figure 5)

Monofocal: A surgical fracture creates a "distraction gap" (the interval between 2 bone surfaces where the healing events will happen) for posterior traction of the separated bone segments. Monofocal DO currently represents most of the clinical applications in the craniofacial skeleton.

Bifocal: A solution of continuity is treated by moving a surgically produced bone segment along the defect, from one extremity to the other. The moving segment is a "transport disc." This approach is used frequently for mandibular reconstructions after tumour ablation [38].

Trifocal: Two transport discs are created from the two extremities of defect and moved until they meet. Usually, major corrections are done with trifocal processes [39].

Distraction devices

Relation with the skin surface

A. External: The external devices are attached to the bone by percutaneous pins connected externally to fixation clamps. The fixation clamps, in turn, are joined together by a distraction rod which when activated, effectively pushes the clamps and the attached bone segments apart, generating new bone in its path.

B. Internal: are placed subcutaneously or within the oral cavity i.e. intra orally. They can be placed above i.e. extra mucosal or below i.e. sub mucosal or buried under the soft tissue. Devices attached to the bone are bone-borne; to the teeth are tooth-borne or attached to the teeth and bones are the hybrid type of distraction appliances.

Type of anchoring tissue

A- Tooth-borne: Supported only by teeth

B- Bone-borne: Anchored exclusively on bone tissue

C- Hybrid: Fixed to both bone and teeth

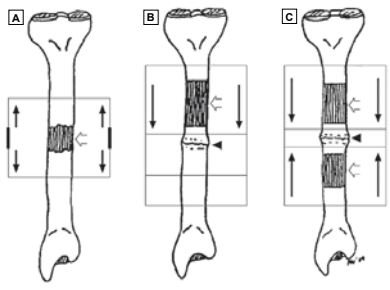

Figure 5: Three types of distraction osteogenesis have been described: Monofocal, bifocal, and trifocal.

Number of vectors of movement

A- Unidirectional: Provides only 1 possible direction of bone movement

B- Bidirectional: Bone can be distracted in 2 directions

C- Multidirectional: Bone can be distracted in more than 2 directions

Types of distractor material

A- Bioresorbable devices: used in infants with congenital disorders

B- non-resorbable, metallic devices

Clinical Implications

The clinical applicability of distraction osteogenesis is dependent upon device-related and tissue-related factors. Device-related factors affect the mechanical integrity of the distractor and the stability of bone fixation [40]. The number, length, and diameter of fixation pins, the rigidity of the distractor fixation, and the material properties of the device affect the clinical result of the distraction procedure [41]. Additionally, the orientation of the distraction device and the resulting distraction vector relative to the anatomical axis of the distracted bone segments (as well as – in the case of jaws – the occlusal plane and the joint position) are important considerations [42]. The significance of device orientation has been established in clinical settings and refinements have been made to optimize the treatment outcome. Tissue-related parameters affecting the quality of the distraction tissue generated include the geometric shape, the cross-sectional area, the density of the distracted bone segments, the length of the distraction gap, and the tension of the soft tissue envelope [43,44]. In Cranio-maxillofacial and alveolar distraction osteogenesis it is important to consider dental aspects in the planning of distraction osteogenesis. These aspects include predistraction orthodontics, osteoto my design and location, selection of the distraction device, orientation of the distraction vector, use of distraction splints, post distraction orthodontics, and functional loading of the generated bone [45,46]. As elongation of the mandible leads to force transmission to the temporo mandibular joints, structural alterations in the anatomy of the joints as well as the overlying soft tissue might also be expected. Distraction procedures should take these joint effects into account [47].

One of the primary planning considerations in maxillofacial distraction osteogenesis is the use of either an external distraction framework or an internal device. Critical to this decision is an evaluation of the goals of the distraction process [48-50]. The external devices have the powerful advantages of allowing bone distraction in three planes and allowing the surgeon to alter the direction, or vector, of the distraction process while the distraction is proceeding. The external distractors allow for easier adjustment of the direction of the distraction. However, the longer the distance from the axial screw of the distractor to the callus, the less effective the distraction. Brunner et al. [41] first reported this principle of "molding the regenerate" in 1995. The "molding" takes advantage of the ability to manipulate the semisolid state of the non-mineralized and hence non rigid, bone in the distraction gap. This allows for "fine-tuning" of the distraction process while the distraction is proceeding, and thus permits dental relationships to be adjusted before the patient enters thec onsolidation phase of bone healing [51]. The external framework also allows greater amounts of ultimate expansion length. Expansions of 40 mm or greater have been reliably obtained. The disadvantages of an external frame distractor are the creation of a facialscar and the increased distance

from the body of the distractor to the bone surface, leading to a longer "moment arm" at the pin-bone interface and an increased possibility of pin loosening. In addition, there is the need for "pin care" by the patient at the percutaneous pin sites [52]. The goal of distraction with internal devices is generally more modest, in the range of 25 mm or less. This is a consequence of the constraints placed on the physical size of the device and the ability to fit it within the mouth. In addition, the direction of the distraction cannot be altered after the device is placed. Development of miniature, internal distraction devices have made this clinically feasible and practical.

There have been numerous studies on the negative effects of aging on osseous regeneration during distraction. The lower the age of the individual, the faster is the bone regeneration. For example, bone formation and mineralization in children undergoing long bone distraction occurs approximately twice as fast as in adults, as assessed by quantitative computed tomographic scanning [52].

Under 2 years of age, mandibular distraction is not usually performed unless there is airway compromise. Mandibular distraction is avoided for several reasons. First, it is difficult to identify tooth buds at this age; therefore, permanent dental injury is a likely occurrence. Second, distraction at this age can be a daunting experience for the patient and the parents. The exception to this would be when early mandibular distraction is used to prevent tracheotomy in a newborn with micrognathia that is causing severe airway obstruction [21]. From age 6 to adolescence, during the period of mixed dentition, orthodontic treatment is needed to promote the growth of the affected dento-alveolus and to aid in the proper eruption of the permanent teeth. Distraction would be considered during this time only if the patient had sleep apnea or had never received any previous surgical treatment. Distraction could be performed if the patient has a significant growth deficiency in the mandible after rib grafting. Mandibular distraction during the teenage years should be postponed until the patient has reached skeletal maturity. Despite a documented decrease in osteogenesis with increasing age, this factor alone is not a contraindication to distraction osteogenesis, because numerous clinical and experimental studies have demonstrated successful long bone and mandibular distraction in older subjects [34]. Thus, this therapeutic method remains an attractive option for the reconstruction of maxillofacial abnormalities in virtually all age groups; nevertheless, variable distraction protocols may be required for optimal bone production.

In younger patients, distraction using the corticotomy of the external cortex is possible because the bone is very soft and pliable. However, in adults it is possible that the distraction device could deviate or distraction could fail due to resistance because the internal cortex does not fracture. Latency, rate, and rhythm of distraction are variables that influence the quality of the regenerate. Of these factors, the effect of latency is the most controversial [53-55]. Most craniofacial surgeons have empirically applied the conclusions from long bone studies and recommend waiting periods of 4 to 7 days following osteotomy and before initiating the distraction process. In younger children, the high rate of bone metabolism favours a shorter waiting period. Some clinicians, however, use a zero latency period and begin distracting right at the time of appliance insertion. They claim no adverse effects on outcome while substantially shortening the treatment period [54]. Waiting too long before distraction (beyond 10 to 14 days) substantially increases the risk of premature bone union. In contrast to latency, the rate and rhythm (frequency) of distraction are believed to be important factors [53]. If widening of the osteotomy site occurs too rapidly (>2 mm per day), then a fibrous non-union will result, whereas if the rate is too slow (<0.5 mm per day), premature bony union prevents lengthening to the desired dimension. These findings in long bones have been empirically applied to the craniofacial skeleton, and most studies have described a rate of 1.0 mm per day. According to Ilizarov's work in long bones, the ideal rhythm of DO is a continuous steady-state separation of the bone fragments [4-7,56]. However, this is impractical from a clinical standpoint, and therefore, most reports recommend distraction frequencies of 1 or 2 times daily. A 1-mm/day rate of distraction (2 × 0.5 mm) and a 5- to 7-day latency seem to be generally accepted as the gold standards in the field of craniofacial distraction osteogenesis [19,57-62]. In the craniofacial skeleton, most authors advocate 4 to 8 weeks, with the general rule that the consolidation period should be at least twice the duration of the distraction phase [39,54,63]. Distraction in load-bearing bones, such as the mandible, is an indication for a longer consolidation time. Appliance rigidity during distraction and consolidation is a critical element to ensure that bending or shearing forces do not result in micro-fractures of the immature columns of new bone within the regenerate, which lead to focal haemorrhage and cartilage interposition [53].

Indications of DO

Current usage falls into 4 broad groups as follows:

a. Lower face (mandible)

1- Unilateral distraction of the ramus, angle, or posterior body for hemifacial microsomia.

2- Bilateral advancement of the body for severe micrognathia, particularly in infants and children with airway obstruction as observed in the Pierre Robin syndrome.

3- Vertical distraction of alveolar segments to correct an uneven occlusal plane or to facilitate implantation into edentulous zones.

4- Horizontal distraction across the midline to correct cross bite deformities or to improve arch form.

5- Transport distraction to generate a neo-condyle and temporo mandibular joint in patients with severe joint ankylosis.

b. Mid face (maxilla, orbits)

1- Advance the lower maxilla at the LeFort I level.

2- Complete midfacial advancement at the LeFort III level.

3- Closure of alveolar cleft associated with cleft lip and palate deformities.

4- Upper face (fronto-orbital, cranial vault).

5- Advancement of the fronto-orbital bandeau, alone or in combination with the mid faceas a monobloc or facial bipartition.

6- New use of distraction as a means of cranial vault remodelling by gradual separationacross resected stenotic sutures.

7- Zygomatic distraction in cases of deficient zygoma.

c. Craniofacial DO include the following

1- Nonsyndromic Craniofacial Syndrome - Coronal (bilateral or unilateral) or sagittal.

2- Syndromic Craniofacial Syndrome (Apert, Crouzon, Pierre Robin syndrome, Treacher Collins syndrome, Goldenhar syndrome, Brodie Syndrome and Pfeiffer syndromes).

3- Facial clefts, cleft lip and palate.

4- Patients with severe severe sleep apnea.

5- Hemifacial microsomia.

6- Bi-maxillary crowding with anterior-posterior deformity.

7- Bimaxillary deficiencies (Lengthening and widening).

8- Facial Asymmetry.

d. Acquired indications

1- Reconstruction of posttraumatic deformities (midfacial retrusion or mandibularcollapse).

2- Insufficient alveolar height and/or width (Maxillary or mandibular alveolar distraction).

3- Reconstruction of oncologic and/or aggressive cystic jaws defects.

Complications of DO

Complications can be divided into 3 groups: A) Intraoperative, B) Intradistraction, and C)

Postdistraction complications.

a. The intraoperative complications concern the surgical procedure (eg, malfracturing, incomplete fracture, nerve damage, and excessive bleeding) and device- relatedproblems (eg, fracture and unstable placement).

b. Intradistraction complications concern those arising during distraction (eg, infection, device problems, pain, malnutrition, and premature consolidation).

c. Postdistraction complications concern the late problems arising during the period of splinting and after removal of the distraction devices (eg, malunion, relapse, andpersistent nerve damage) [54,61].

Maxillofacial application

Dento-alveolar distraction: One of the interesting applications of the bone transport technique is the augmentation of the maxillary and mandibular alveolar ridges. These deformities were managed by a variety of surgical techniques, such as autogenous on lay bone grafting, alloplastic augmentation, connective tissue grafting or guided tissue regeneration. Each of these modalities, however, had their limitations [64,65].

Alternatively, osteodistraction of the alveolar process provides superior reconstruction of these types of defects. Block and co-workers established the validity of distraction osteogenesis for alveolar ridge augmentation in canine mandible [65].

In 1996, Chin and Toth reported the first clinical application of vertical mandibular alveolar distraction osteogenesis. Following the clinical introduction of alveolar ridge distraction by Chin, the use of the technique, as well as the number of available devices, has increased tremendously [53].

Small alveolar deficiencies such as alveolar cleft are also capable of being treated through both horizontal and vertical elongation of the deficient alveolus. If carefully planned in conjunction with an orthodontist, a single tooth or an entire segment containing teeth can be carefully advanced into a more anatomic position without risking devascularisation of the dental roots. This can potentially accelerate the correction of significant dental malocclusion; in some cases, it obviates the need for extensive oral surgical procedures [66].

Periodontal ligament distraction: Another interesting modification of the bone transport technique has been experimentally and clinically applied by Liou and Huang [67]. This method is based on distraction of the periodontal ligament and is referred to as rapid canine retraction. Briefly, the technique involves premolar extraction followed by undermining of the interseptal bone distal to the canine to reduce bony resistance on the compression side. Next, the periodontal ligament is gradually stretched via distraction of the tooth-bearing segment and new bone is created mesial to the distally moving tooth. Importantly this is distinctly different from tooth movement into regenerate bone. The former involves movement of both a tooth and bone as new bone is generated, whereas the latter involves remodelling of bone as a tooth is moved into new bone [67].

Mandibular distraction: Snyder et al. using an external distractor, primarily investigated the gradual distraction of mandible in canines. This was the first report demonstrating the application of Ilizarov's principles in the craniofacial skeleton [68]. McCarthy et al. were the first to clinically apply extraoral distraction osteogenesis on 4 boys with congenital anomalies such as hemifacial microsomia and Nager's syndrome [9,11]. Guerrero, whilst using an intraoral tooth-borne hyrax-type device in patients with transverse deficiencies developed a midsymphyseal mandibular widening technique [69]. Though the application of osteodistraction to the human craniofacial skeleton demonstrated successful results, the first extraoral devices were capable of only unidirectional mandibular lengthening, either horizontal or vertical. Unidirectional mandibular lengthening provided complete correction of linear discrepancies only. However several deformities often involve the ramus, the corpus, and the angle of the mandible. Restoration of the mandible in such cases requires multidirectional devices. Molina and Ortiz-Monasterio were the first to use bidirectional osteodistraction in the mandible by creating two distraction sites via double-level corticotomies; this enabled them to lengthen both the parts of the mandible simultaneously. In order to correct mandibular deformities in three- dimensions, independent lengthening of mandibular corpus and ramus must be combined with gradual angular adjustments. As a result, several multidirectional distraction devices were developed, thereby allowing manipulation of bone segments in multiple planes of space [70].

The initial development of intraoral mandibular distraction devices progressed in two directions (1) miniaturization of external devices, (2) modification of available orthodontic devices. The major advantages of the intraoral devices were the inconspicuous nature of the devices and absence of facial scars. However intraoral devices have design limitations primarily related to the limited size of the device and restricted access to the oral cavity. Due to these limitations, further development of intraoral devices took an alternative approach. They were (1) the design of specialized devices based on anatomic location or clinical application. (2) The development of a universal device adaptable to any situation in the craniofacial region. (3) The fabrication of a custom made, individually pre-programmed device.

Similar to the development of the extra oral devices, recently developed intraoral devices have evolved from unidirectional to bidirectional to multidirectional distraction. Walker developed a bidirectional buried mandibular distractor that allows mediolateral adjustments during bilateral sagittal mandibular distraction [71,72] and Triaca et al. developed the Multi-Axis Intraoral Distractor, the only truly three-dimensional intraoral distractors available today [73]. Many

other recent developmental advances include curvilinear, motorized, and hydraulic distraction devices. The curvilinear distractors allow sagittal distraction along the curvilinear path that closely mimics the natural growth pattern of the mandible. Motorized and hydraulic distractors with remote activation and monitoring allow precise directional control, as well as calibration of distraction forces. This simplifies the distraction activation procedure for patients and parents.

A technique termed transport distraction has also been described to generate a neo-condyle and temporomandibular joint in patients with severe joint ankylosis. A gap arthroplasty was first performed through a Preauricular incision to excise the regions of abnormal bone fusion and to reduce condylar height. A vertical or L-shaped osteotomy was made from the medial aspect of the projected condyle down to the posterior aspect of the ramus. After a 5-day latency period, the osteotomized segment of bone was distracted and transported in a vertical direction into the glenoid fossa. During the activation phase, the edge of the neo-condyle was remodelled into a smooth, rounded surface. Fibro-cartilaginous tissue at the leading edge of this segment acts as a pseudodisc. Distraction was continued until articulation was achieved and vertical lengthening of the mandible was adequate. The typical 8-week consolidation period was observed, but vigorous temporo mandibular joint exercises were initiated 1 week post-cessation of device activation. This method produces a vertically elongated mandible with a functioning, non ankylosing temporo mandibular joint in the short term [74].

Maxillary and midface distraction

In 1993, Rachmiel et al. first demonstrated the possibility of maxillary distraction in their study; they performed mid face gradual advancement on five sheep [75]. In 1995, Block et al. demonstrated anterior maxillary advancement using tooth-borne distraction devices in dogs [76].

In 1996, Rachmiel et al. reported on multiple segmental distraction of the facial skeleton in three young adult sheep [77]. The results of the study indicated that multiple segmental distractions may provide improved three-dimensional control correction of complex facial deformities.

Maxillary distraction has also been experimentally evaluated by Carls and colleagues as a potential treatment for velopharyngeal incompetence [78]. They believed that distracting the hard palate toward the posterior pharyngeal wall would eliminate velopharyngeal incompetence, provided that the short soft palate had satisfactory muscle function.

One of the first clinical applications of midface distraction in humans was reported by Polley et al., which used an externally fixed cranial halo to distract the midface. The advantages of Rigid External Distraction (RED) are that it is a fairly simple technique to apply intra-operatively, it is easy to activate for patients and can be removed without the need for a second operative procedure at the completion of consolidation [79]. Figueroa et al. demonstrated that full correction of the midface deficiency, including both the skeletal and soft tissue deficiency, was possible with their technique [80,81].

Bone transport

Bone transport is a distraction osteogenesis technique for treating long bone defects that result from trauma, oncologic resection, or congenital anomalies. The concept includes resection of a pathologic bone followed by gradual transport of an osteotomized healthy bone segment (transport disk) via a distraction device across the area of defect. As the transport bone segment is advanced new bone tissue is generated, gradually filling the defect. After the transport disk reaches the opposite host bone segment, the intervening fibrous tissue is removed followed by application of compression between the transport and host bone segments at the docking site.

In 1990, Constantino et al. demonstrated the feasibility of bone transport techniques for segmental mandibular regeneration using a canine model [82,83]. Segmental mandibular defects (25 mm) were first created and then transported over a 25 day period and a regenerate bone was formed using bifocal and trifocal bone transport.

In 1995, Constantino et al., successfully applied transport distraction to restore the continuity of a mandibular defect formed as a result of cancer resection following radiation therapy in a patient [84]. Block et al. presented the results of four cases with bone transport using a Synthes lengthening device [85]. Since then, bone transport has been sporadically used to treat bone defects caused by trauma or bone resection.

Cranial distraction

The first experimental investigation on cranial osteodistraction was performed in 1957 by Polezhaev [86]. They demonstrated that a critical-size skull defect could be filled with regenerate bone by transporting an osteotomized bone segment across the defect.

Various external and internal devices have been designed for use in cranial distraction in which cranial and midface distraction has been successfully conducted for correcting craniofacial deformities of various degrees like Crouzon's syndrome, Apert's syndrome, Pfeiffer's syndrome and midface abnormalities secondary to craniofacial anomalies. Simultaneous midface and forehead distraction using internal devices after Le Fort IV osteotomy has also been reported [87].

Conclusion

Distraction osteogenesis of the craniofacial skeleton has become increasingly popular as an alternative to many conventional orthognathic surgical procedures.With the modern technology for the construction and manufacture of dental equipment and instruments, more delicate distractors were done. The indications for use have grown for the most diverse types of bones deformities.

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