https://doi.org/10.48047/AFJBS.6.14.2024.12023-12045

African Journal of Biological Sciences

Research Paper Open Access

DISTRACTION OSTEOGENESIS: INNOVATIONS IN HARNESSING CLINICAL BENEFITS AND BIOLOGICAL INSIGHTS FOR ORTHODONTIC AND ORAL SURGICAL CARE

RICHA WADHAWAN [1], AKANSH DATTA [2], GUNJAN KAUSHIK [3], LT COL KULDIP SINGH [4] , VIKASH KUMAR KIRAR [5], MEGHNA VERMA [6]

[1] PROFESSOR, ORAL MEDICINE, DIAGNOSIS & RADIOLOGY, PDM DENTAL COLLEGE & RESEARCH INSTITUTE, BAHADURGARH, HARYANA wadhawanricha1@gmail.com

[2] READER, ORAL AND MAXILLOFACIAL SURGERY, TEERTHANKER, MAHAVEER DENTAL COLLEGE AND RESEARCH CENTRE, MORADABAD, UTTAR PRADESH drakansh.dental@tmu.ac.in

[3] SENIOR LECTURER, ORTHODONTICS & DENTOFACIAL ORTHOPAEDICS, MAHARANA PRATAP COLLEGE OF DENTISTRY & RESEARCH CENTRE, GWALIOR, MADHYA PRADESH kaushikgunjan495@gmail.com

[4] DENTAL SURGEON, ORTHODONTICS & DENTOFACIAL ORTHOPAEDICS, GOVERNMENT OF UTTAR PRADESH, JHANSI, UTTAR PRADESH dr.kuldeeptomar@gmail.com

[5] POST GRADUATE, ORAL & MAXILLOFACIAL SURGERY, MAHARANA PRATAP COLLEGE OF DENTISTRY & RESEARCH CENTRE, GWALIOR, MADHYA PRADESH vikashkumarkirar@gmail.com

[6] POST GRADUATE, ORAL AND MAXILLOFACIAL SURGERY, SHREE BANKEY BIHARI DENTAL COLLEGE & RESEARCH CENTRE, GHAZIABAD, UTTAR PRADESH meghverma26@gmail.com

Corresponding author: wadhawanricha1@gmail.com

Article History Volume 6, Issue 14,

2024 Received : 11 Jun 2024

Accepted : 05 July 2024

Published: 12 Sep 2024

doi: 10.48047/AFJBS.6.14.2024.12023-12045

ABSTRACT

Introduction

Distraction osteogenesis (DO) is a transformative surgical technique used for bone lengthening and regeneration. It has revolutionized orthodontic and oral surgical practices by allowing controlled bone growth through mechanical distraction. Recent advancements in materials, devices, and digital planning have further enhanced the efficacy of DO, leading to improved patient outcomes and reduced complications. This systematic review aims to evaluate these innovations, highlighting their clinical benefits and biological insights.

Methods

A comprehensive search was performed across electronic databases, including PubMed, Scopus, Embase, Cochrane Library, and Web of Science. Search terms included "distraction osteogenesis," "orthodontics," "oral surgery," and "bone regeneration." The review included peer-reviewed clinical trials, cohort studies, case-control studies, and review articles published from 1990 to 2024, focusing on the biological mechanisms, innovations, and clinical outcomes associated with DO. Data extraction and risk of bias assessment were conducted by independent reviewers, with findings synthesized qualitatively and quantitatively.

Results

Innovations in distraction osteogenesis, such as advancements in device technology and materials, have significantly improved surgical precision and patient outcomes. The integration of digital planning and bioabsorbable materials has reduced complications and enhanced comfort. Biological insights into mechanotransduction and the role of growth factors have accelerated bone formation and optimized treatment protocols. Clinical applications of DO have expanded to include temporomandibular joint conditions, demonstrating effective results across a variety of cases.

Discussion

The advancements in distraction osteogenesis have led to more precise and effective treatments, reducing risks and improving patient satisfaction. The development of new devices and techniques, combined with deeper biological understanding, has refined the process of bone regeneration. Despite these improvements, challenges such as scarring and post-operative complications remain. Future research should focus on further innovations in surgical techniques, materials, and biological therapies to enhance the efficacy and applicability of DO in clinical practice.

Keywords: Distraction osteogenesis, Dentofacial orthopedics, Orthodontics, Tissue engineering, Bone regeneration, Mechanotransduction, Cellular mechanisms

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Introduction

Distraction osteogenesis (DO) represents a major advance in bone surgery techniques, particularly in orthodontic and oral surgery. This approach, which involves gradually breaking down bone to stimulate new bone formation, has been revolutionized by advances in medical and biological understanding [1]. DO has applications beyond its original use of lengthening the body to eliminate spaces between bones and teeth, and provides significant benefits to patient care. Recent innovations have transformed the way osteogenesis intervention is used, improving outcomes, and expanding its range of applications [2]. Advances in modern technology, such as more core materials and bioabsorbable materials, has resulted in improved patient outcomes by doubling the need for surgery and reducing subsequent discomfort. Additionally, the integration of digital plans and precision instruments improves the assembly and adjustment of traction devices, optimizing the functionality and aesthetics of the process. The clinical benefits of interventional osteogenesis are significant [3]. DO gently correct bony deformities and facial asymmetry, enabling less invasive orthognathic surgery. Innovations in this field allow for the prediction and control of clinical outcomes and the reduction of risks associated with bone grafting and other related procedures [4]. Advances in generation in affected character-specific making plans and gadget improvements assist advantage better outcomes and enhance medical consequences. The biological mechanisms of osteogenesis intervention have also developed with contemporary studies. Advances in records the mechanisms of bone formation, which includes the location of mechanotransduction and cell responses to mechanical stress, have actually set up that dissolved oxygen induces new bone formation [5]. New traits in regenerative medication, along with the usage of growth factors and stem mobile remedy, are being investigated to beautify this process with the ability to enhance bone nice and shorten treatment time [6]. Distraction osteogenesis has amazing blessings in orthodontic remedy and oral surgical treatment. For dentists, the potential to deal with huge bone conflicts and help the boom of growing sufferers opens up new opportunities in remedy making plans. Oral surgeons have benefited from the reduced rate of bone grafting surgical operation and the multiplied accuracy in treating jaw and facial deformities [7]. The mixture of these improvements not only will increase the efficiency of surgical operation however additionally enhances affected character comfort and healing. As the sphere keeps decorating, ongoing studies and technological advances have to in addition refine interventional osteogenesis technology, expand its packages, and enhance patient results [8]. The mixing of clinical effects and biologic information is informing the improvement of this new approach to orthodontic dentistry and oral surgery. Intraoral distraction osteogenesis and distraction histogenesis (DH) are advanced surgical methods designed to increase or repair the bone and gentle tissue of the stomatognathic body [9]. This technique makes use of traction control to cut up bone in order to stimulate new bone and tissue formation via osteogenesis and histogenesis [10]. The strategies of this approach date back to pioneers which includes Hippocrates, Codvilla and Gavriil Ilizarov [11]. DO became first applied to the human mandible in 1992 through McCarthy et al., with modern-day changes together with "Dental Distraction" with the useful resource of Liou and Huang and "Dentoalveolar Distraction" thru Iseri et al. make bigger the scope of software [12]. Clinically, DO has been shown to be powerful in many conditions including congenital and inherited jaw anomalies, midface and malar troubles, cranium reconstruction and condylar repair of temporomandibular joint ankylosis, and facial accidents [13]. It refers to numerous sorts of teeth and bites, together with Pierre-Robin syndrome, Goldenhar syndrome, and Treacher Collins

syndrome, in addition to symptoms inclusive of cranial hypoplasia and non-syndromic bimaxillary shortening, in addition to symptoms associated with obstructive sleep apnea [14]. Despite the facts that DO are effective in accelerating tooth recovery and lowering the recurrence of histogenesis, it additionally has some risks, consisting of mistaken remedy, scarring, ache, and oral headaches [15]. However, advances in three-dimensional management tools have extended accuracy and decreased damaging outcomes. When figuring out the timing of orthodontic remedy for osteogenesis intervention, the method will vary in keeping with the affected person's specific state of affairs [16]. Pre-orthodontic remedy stabilizes the dental arch, guarantees the connection among the tooth, and enables expecting traction surgical treatment. This method also allows early practice of the final occlusal relationship and reduces the difficulty of publish-intervention modifications. But, cautious time control is needed to keep away from interfering with the DO method, and therefore precise coordination is needed [17]. Alternatively, post-dental treatment lets in the right healing of the enamel and chew even as the bone is reshaped and stabilized by means of the DO [18]. This technique takes into consideration all changes and optimizes the very last end result while the bone is processed. Although it delays the total recuperation time and should be carefully coordinated with the DO stage to prevent new bone formation, it allows adjustment and improves the consequences. Ultimately, the decision regarding pre- and post-dental treatment should be primarily based on a thorough assessment by the dentist and oral specialist, considering factors such as the patient's age, the extent of intervention needed, and overall health condition [19].

Methodology This systematic review aims to evaluate the innovations in distraction osteogenesis (DO) and explore their clinical benefits and biological insights for orthodontic and oral surgical care. The methodology follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines.

Search Strategy

A comprehensive search of electronic databases, including PubMed, Scopus, Embase, Cochrane Library, and Web of Science, was conducted. The search terms used include "distraction osteogenesis," "orthodontics," "oral surgery," "bone regeneration," "maxillofacial surgery," "clinical outcomes," and "biological insights." The search was limited to studies published in English from 1990 to 2024.

Inclusion Criteria

- Peer-reviewed clinical trials, cohort studies, case-control studies, case series, and review articles focusing on distraction osteogenesis in orthodontic and oral surgical care.
- Studies evaluating the biological mechanisms, innovations in techniques, devices, and materials used in distraction osteogenesis.
- Articles that address the clinical benefits, complications, and long-term outcomes of DO.
- Studies with a follow-up period of at least six months.

Exclusion Criteria

- Studies not related to orthodontic or oral surgical applications of distraction osteogenesis.
- Articles that lack a focus on innovations or biological mechanisms.
- Non-peer-reviewed articles, conference abstracts, and editorials.
- Animal studies or in vitro studies that do not translate directly into clinical applications.

Data Extraction and Management

Two independent reviewers extracted data from the selected articles. Information extracted included study design, sample size, patient demographics, type of distraction osteogenesis performed, innovations in techniques or devices, biological insights, clinical outcomes, follow-up duration, and complications. Any disagreements between reviewers were resolved through discussion or consultation with a third reviewer.

Risk of Bias Assessment

The risk of bias was assessed using the Cochrane Risk of Bias Tool for randomized controlled trials and the Newcastle-Ottawa Scale for observational studies. Studies were categorized as having a low, moderate, or high risk of bias.

Data Synthesis and Analysis

Data were synthesized qualitatively due to the expected heterogeneity in study designs, clinical applications, and outcome measures. A narrative synthesis was conducted, with a focus on identifying recurring themes and trends in innovations, biological mechanisms, and clinical outcomes. Meta-analysis was considered when a sufficient number of homogeneous studies with comparable outcome measures were identified. The Review Manager (RevMan) software was used for any quantitative synthesis.

Outcome Measures

Primary outcome measures included the success rates of distraction osteogenesis in orthodontic and oral surgical applications, patient satisfaction, and complication rates. Secondary outcomes included the biological insights gained from various DO techniques and their long-term clinical implications for bone regeneration and craniofacial growth.

Ethical Considerations

This systematic review utilized data from previously published studies and did not involve any direct contact with human subjects. Therefore, ethical approval was not required.

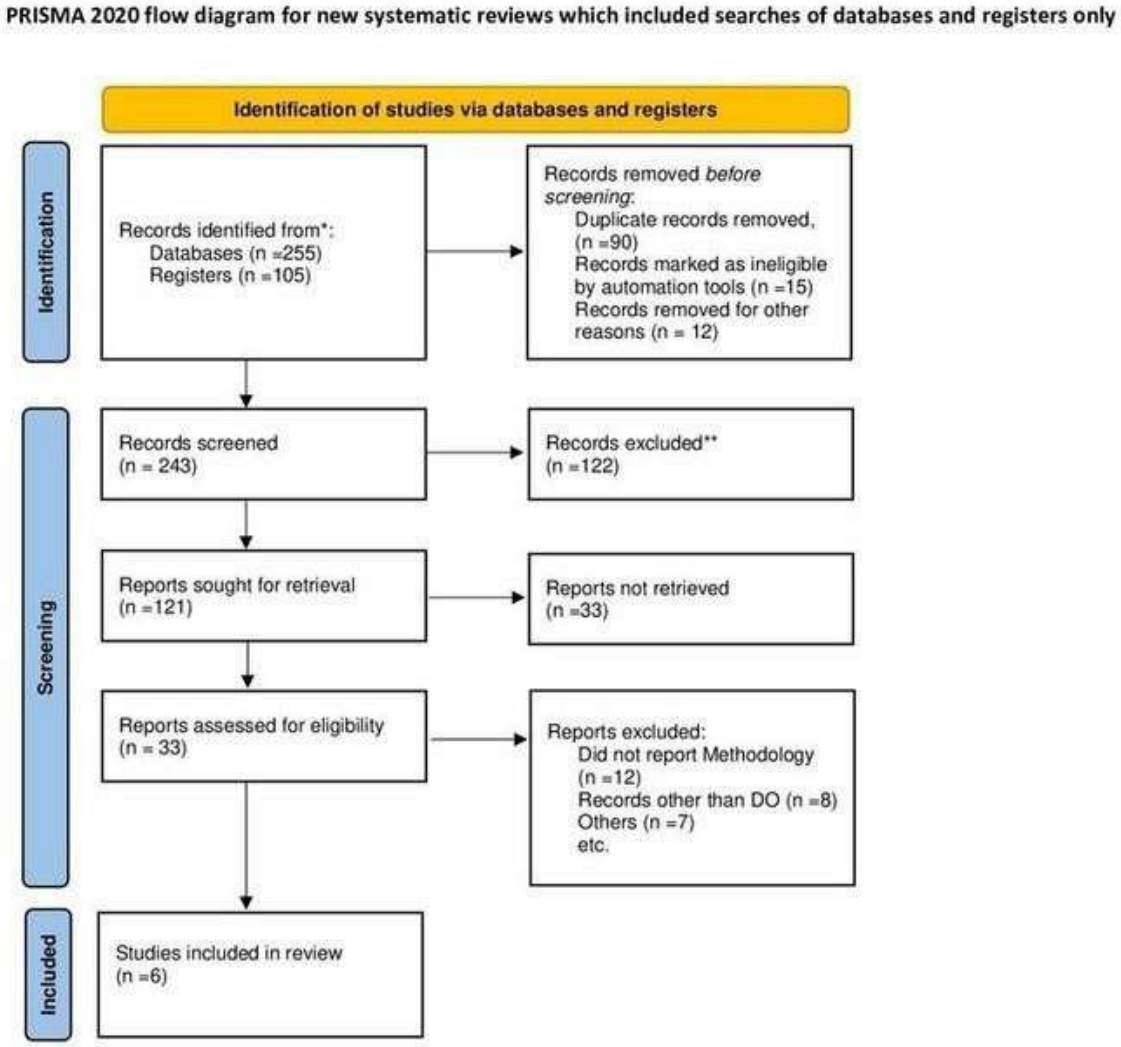

Figure 1: Prisma flowchart of the study

Discussion Distraction osteogenesis (DO) makes use of specialized gadgets called distractors to often separate bones or enamel thru a screw mechanism, facilitating bone movement over numerous weeks. In maxillofacial surgical procedure, those distractors are classified with the useful resource of area (e.g., mandibular, midface, maxillary, alveolar, or transport) and function (e.g., inflexible external distractors (REDs) and internal distractors) [20] (Figure 2).

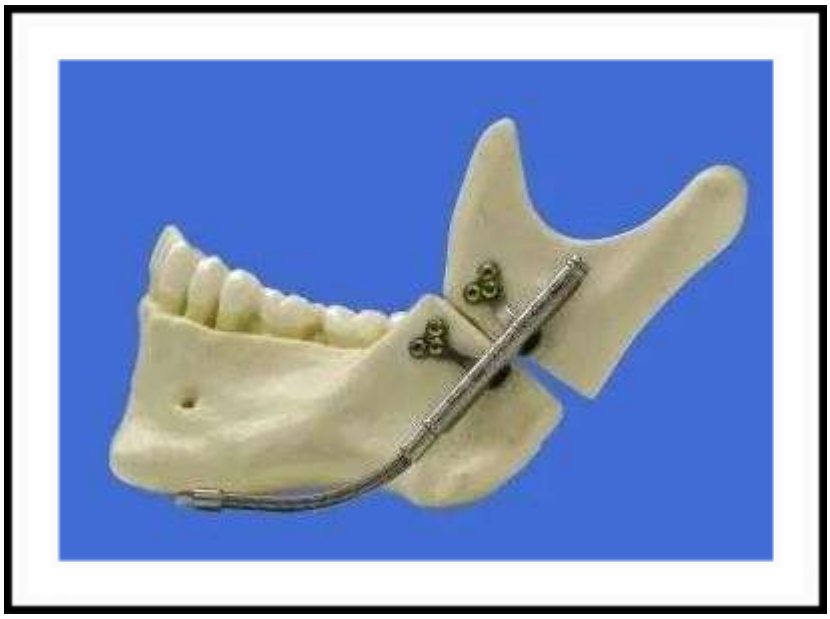

Figure 2: Image depicting Distraction Osteogenesis

Out of doors distractors can be unidirectional, bidirectional, or multiplanar and are linked with various methods and substances, even as inner distractors, positioned below or above the mucosa, consist of mandibular intraoral distractors, modular inner distractors (MID), and enamel-supported distractors [21]. Techniques consisting of callotasis and distraction epiphysiolysis facilitate bone lengthening and increase plate manipulation. The effectiveness of DO hinges on unique control of each mechanical and biological force, with the purposeful matrix precept highlighting the function of surrounding smooth tissues and neuromuscular systems in shaping new bone [22]. The choice and location of distraction gadgets on the mandible or maxilla are brought on by means of manner of elements which include organic and mechanical forces affecting the regenerate, which need to be carefully controlled to obtain the desired adjustments in form and feature. Mechanical forces from occlusion, the layout and activation of distraction devices, and orthodontic auxiliaries' impact tissue morphology, aligning with orthodontic desires of structural integrity, useful optimization, and aesthetics [23]. Strong fixation of osteotomized bone segments is essential, and the distraction axis ought to align with the anatomical axis of the bone to save you negative joint loading [24]. Clinical studies suggest that skeletal morphology modifications are stimulated through the tool's orientation relative to the mandible, with placements categorized as vertical, horizontal, or indirect. The ranges of DO—osteotomy, latency, distraction, and transforming and consolidation —contain unique natural and mechanical concerns [25]. Osteotomy calls for enough live osteocytes, with corticotomy regularly favored in well-vascularized craniofacial areas [26]. The latency section sees gentle callus formation, observed with the useful resource of distraction, in which modern-day traction creates a microenvironment that promotes new tissue boom [27]. The transforming and consolidation segment involves bone maturation and gentle tissue variation, with the newly original bone in the end corresponding to preexisting bone via intramembranous ossification [28]. The way consists of the fibrous imperative place, transition location, reworking location, and mature location, with mechanical transduction playing an essential role. Extremely good from fracture restore, DO involves regulated microtrauma and intramembranous ossification in place of endochondral ossification [29]. Table 1 shows the overview of Studies.

Table 1: Summary of References and Main Findings for Systematic Review on Distraction Osteogenesis

Reference	Study Focus	Journal	Year	Main Findings
Ilizarov GA	The principles of the Ilizarov method	Bull Hosp Jt Dis Orthop Inst	1988	Demonstrated the ability to promote bone lengthening and regeneration using mechanical stimulation.
Maull DJ	Review of devices for traction osteogenesis of the craniofacial complex	Semin Orthod	1997	Provided a comparative review of devices and suggested improved outcomes with intraoral devices.
McCormick	Reconstruction of the mandibular condyle using distraction osteogenesis	J Craniofac Surg	1999	Highlighted successful reconstruction of the mandibular condyle using distraction osteogenesis.
Battagel JM	Transport distraction osteogenesis in orthodontically treated Class III malocclusions	Br J Orthod	1994	Identified key factors predicting relapse, emphasizing the importance of long-term follow-up in treatment.
Cohen SR, Simms C, Burstein FD	Mandibular distraction osteogenesis in the treatment of upper airway obstruction in children	Plast Surg Reconstr	1998	Demonstrated the efficacy of mandibular distraction osteogenesis in improving airway patency in pediatric patients.
Guerrero CA	Intraoral mandibular distraction osteogenesis	J Oral Maxillofac Surg	1992	Discussed the advantages of intraoral approaches in mandibular distraction for avoiding scarring and improving outcomes.

Molecular Mechanisms: DO/DH harnesses the regenerative capacities of musculoskeletal tissues, guided with the aid of advanced techniques together with subsequent-era sequencing and proteomics [30]. Mechanical tension affects crucial signaling pathways, which includes bone morphogenetic proteins (BMPs), inflammatory and vascular proteins, and epigenetic factors [31]. In DH, inflammatory responses and seasoned-inflammatory genes like prostaglandins and COX2 play important roles in retaining bone balance. Techniques like pulsed electromagnetic discipline (PEMF), ultrasound, and surprise wave therapy beautify bone transforming. Tensile pressure affects immune responses and mechanotransduction pathways crucial for bone stability and nerve regeneration [32]. Key mechanisms consist of elevated Hippo signaling, nuclear proto-oncogene proteins, C-fos, C-jun, and BMPs all through consolidation [33]. Endothelial progenitor cells (EPCs), activated thru VEGF receptors, and is vital for brand new blood vessel formation and bone production [34]. Research into boom hormones, EP2-precise agonists, thrombin peptide 508 (TP 508), small noncoding RNAs (miRNAs), and superior scaffolding substances keeps to improve bone development and consolidation. In maxillofacial distraction osteogenesis, the success of the procedure hinges on elements together with the design, configuration, durability, balance of the distraction tool, and its orientation relative to anatomical axes [35]. Tissue-related components, which include bone geometry, density, shipping hole length, and muscle anxiety, considerably impact consequences. The choice among external and inner gadgets is important [36]. External devices offer three-dimensional transport competencies however may additionally result in facial scarring and limited flexibility. Inner devices, with their smaller length and ease of application, permit for specific adjustments and management. Distraction strategies are usually deferred in growing patients and blended with corticotomy in more youthful people. For adults, starting distraction four to 7 days after osteotomy is suggested to limit the chance of untimely bone union. The appropriate latency period is 5 to 7 days, with a conventional distraction price of 1 mm in line with day [37]. Dento-Alveolar Distraction: In 1996, Chin and Toth pioneered vertical mandibular alveolar distraction osteogenesis, confirmed thru Block and co-workers. This method excels in 3-dimensional reconstruction of the alveolar ridge, especially inside the mandibular canine place, supplying superior effects in comparison to conventional grafting and tissue regeneration strategies [38]. It's miles effective for growing alveolar ridge bone quantity for implants or orthodontic movements. The thoughts of Ilizarov's bone lengthening had been tailored for facial programs by using the usage of Snyder, McCarthy, and Guerrero, reaping advantages patients with facial dysmorphism, breathing issues, and various congenital and placed up-surgical conditions [39]. Distraction-based strategies provide advantages which include in advance intervention, decreased procedure instances, fewer complications, and a minimized want for added surgical tactics. Periodontal Ligament Distraction, introduced via way of Liou and Huang in 1998, includes osteogenesis for the duration of rapid orthodontic tooth movement, much like midpalatal suture expansion [40]. Activation at 1 mm/day, combined with interseptal bone fracture, can reduce orthodontic treatment time via the usage of three to four months. Polley et al. pioneered using a hard and rapid cranial halo for midface distraction, notably advancing maxillofacial and midface applications [41]. Maxillary Le castle I distraction addresses retrusion or protrusion problems, especially in patients with cleft lip and palate, at the equal time as Le fortress III distraction manages midface retrusion, breathing issues, malocclusion, and intense dysmorphism in conditions like craniofacial synostosis and microsomia [42]. Cranial distraction, first studied through Polezhaev, makes use of outside frames or internal devices for simultaneous midface and

brow distraction following a Le citadel IV osteotomy [43]. It is indicated for a number of craniofacial deformities, including Crouzon's, Apert's, Pfeiffer's syndromes, and midface abnormalities. Orthodontics in Distraction stages: Pre-distraction orthodontics includes leveling, alignment, and arch coordination [44]. For the duration of the distraction and consolidation levels, intramaxillary and intermaxillary elastics, mini implants, and headgear are used to guide movement and manage rotations of distracted segments [45]. Publish-distraction orthodontics focuses on completing occlusion, aligning roots, and ensuring useful and aesthetic consequences. Retention is done with constant or removable retainers. Bone Regeneration and growth elements: Studies show that when 4 days of consolidation, regenerated bone indicates extended levels of osteocalcin, type I collagen, and BMP-2 and BMP-four. ECM proteins and growth factors like recombinant human fibroblast increase issue (FGF) decorate bone formation. Powerful osteogenesis depends on shielding the periosteum and endosteum from damage and ensuring a healthful blood deliver to the distraction web page. Arterial insufficiency can lead to suboptimal collagen patterns, while limited venous outflow can cause cystic degeneration. A corticotomy should be performed carefully to keep periosteal and endosteal integrity for powerful bone regeneration [46].

Futuristic Considerations: Orthodontists, with their deep understanding of biomechanics and patient care, are preferably positioned to leverage distraction osteogenesis (DO) efficiently. As DO profits scientific traction, staying up to date on advancements in inner distraction devices and incorporating them into treatment plans becomes vital. The fulfillment of DO, much like other orthognathic surgeries, is predicated on sturdy collaboration between surgeons and orthodontists. This interdisciplinary approach is essential for optimizing outcomes in lengthening mandibles and other craniofacial bones. Looking forward, DO and DH techniques promise to extend their effect past craniofacial surgical operation [47]. They could revolutionize the control of osteoarthritis (OA) by using assuaging joint cartilage pressure, reducing inflammation and pain, and selling angiogenesis and recovery. The progress in internal distractors, which address the limitations of long-term external devices, is expected to improve these benefits. Moreover, DO/DH techniques may additionally transform treatments for vascular and circulatory disorders. Research by Qu et al. suggests their ability in dealing with thromboangiitis obliterans and likely diabetic ulcers. Kong et al. are expecting that future studies will advance our expertise of tissue regeneration, such as neural repair in vascular and neurological conditions. Emerging advancements include integrating endoscopic strategies for minimally invasive osteotomies and distraction device insertion. The use of bioresorbable substances may additionally eliminate the want for tool elimination, leaving no hint of insertion. Moreover, microprocessors and miniature motorized distraction devices ought to allow automobile-distraction based on preprogrammed records, further improving medical results. Persevered exploration of these improvements may be pivotal in optimizing healing packages and improving patient care [48].

Conclusion

DO stays and powerful technique for bone lengthening and reconstruction, imparting big advantages for each pre- and post-operative packages. The selection among pre- and postorthopedic distraction strategies depends on patient-precise elements, scientific eventualities, and treatment dreams. Pre-Ortho Distraction Osteogenesis, beginning earlier than orthopedic intervention, permits for early correction of deformities and can lessen the want for extra invasive approaches later. It's especially beneficial for congenital deformities or asymmetries, providing managed and gradual bone lengthening, even though it demands meticulous planning and management to optimize outcomes and decrease complications.

Conversely, put up-ortho distraction osteogenesis, carried out after initial orthopedic surgical treatment, refines or corrects residual deformities, complements stability, and gives additional lengthening whilst the primary surgical treatment is insufficient or in addition lengthening is necessary. This technique may also involve a greater complicated healing and an multiplied risk of complications because of the additional surgical treatment. Each tactics have wonderful benefits and demanding situations and the choice need to be individualized based totally on the patient's condition, the specific deformity, and average remedy targets. Improvements in surgical techniques and technology are usually enhancing the effectiveness of distraction osteogenesis and expanding its packages. Destiny studies and clinical trials are crucial for refining these strategies, optimizing remedy protocols, and knowledge of long-time period outcomes. Clinicians need to stay knowledgeable about the trendy tendencies and combine proof-based practices to provide the exceptional possible patient care.

Financial support and sponsorship : Nil

Conflicts of interest : There are no conflicts of interest

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