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Filippino Lippi. Tobias and the Angel, c. 1475/80. 32.7 x 23.5 cm. National Gallery of Art, Washington, DC, Samuel H. Kress Collection

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Review

ORTHODONTIC AND ORTHOPEDIC EFFECTS OF RAPID MAXILLARY EXPANSION: A NARRATIVE REVIEW OF THE LITERATURE

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ABSTRACT

Background: Rapid Maxillary Expansion (RME) is an orthopedic and orthodontic procedure used to correct transverse maxillary deficiency, a frequent skeletal malocclusion associated with posterior crossbite and airway space reduction. *Methods:*A narrative review was conducted through a systematic search of PubMed, Scopus, and Cochrane Library databases (2020–2025) using the keywords palatal expander, rapid maxillary expansion, MARPE, surgically assisted rapid palatal expansion, and Leaf Expander. Human studies evaluating biological, skeletal, and dentoalveolar outcomes of expansion were included. Sixty-three studies met the inclusion criteria. *Results:* RME produces orthopedic and dentoalveolar effects that vary with skeletal maturity, appliance type, and activation protocol. Tooth-borne expanders (Hyrax, Haas) are effective in growing patients but may cause buccal tipping and mucosal irritation. New NiTi-based expanders, such as the Leaf Expander, generate continuous, low-intensity forces that enhance comfort, biological compatibility, and treatment compliance. Miniscrew-Assisted Rapid Palatal Expansion (MARPE) transfers forces directly to the basal bone, achieving true skeletal separation in late adolescents and adults while reducing periodontal stress. Surgically Assisted Rapid Palatal Expansion (SARPE) remains the most predictable technique for adult patients. *Conclusions:* RME is a well-established orthopedic approach integrating skeletal efficiency, airway improvement, and patient-centered design. Appliance selection should be guided by skeletal maturity and clinical needs. Emerging technologies such as MARPE and NiTi expanders represent a new era of controlled, stable, and minimally invasive maxillary expansion.

KEYWORDS: *Rapid maxillary expansion, palatal expander, MARPE, Leaf Expander, SARPE, orthodontics, craniofacial orthopedics*

INTRODUCTION

Rapid Maxillary Expansion (RME) is a well-established orthodontic and orthopedic procedure designed to correct transverse maxillary deficiency, a common skeletal malocclusion that can lead to posterior crossbite, teeth crowding and non-proper nasal breathing. It was first introduced by Angell in 1860 and redefined by Haas in the 1960s, this technique has since become a cornerstone of interceptive orthodontics and dentofacial orthopedics (1).

RME involved heavy, intermittent forces to the maxillary arch through a central screw mechanism, managing a skeletal disjunction at the midpalatal suture. However, the effects of expansion are not limited to the midpalatal region:

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RME also influences the circumzygomatic, circummaxillary, and pterygopalatine sutural systems, producing a complex orthopedic response that affects both the maxilla and the craniofacial complex.

When the two halves of the maxillary palatal bone are separated, new bone formation occurs within the expansion gap through intramembranous ossification, re-establishing sutural continuity typically within 3 to 6 months (2).

The expansion not only improves arch width and occlusal relationships but also produces beneficial effects on nasal airflow and airway resistance, thereby enhancing respiratory function and overall craniofacial balance (3,4).

Over the decades, various activation protocols and appliance designs have been developed to optimize skeletal efficiency and patient comfort. Traditional tooth-borne expanders, such as the Hyrax and Haas, have been widely used in growing patients, while the introduction of miniscrew-assisted rapid palatal expansion (MARPE) has extended the applicability of the technique to late adolescents and adults, overcoming the limitations of sutural ossification.

More recently, innovative devices such as the Leaf Expander and NiTi-based expanders have emerged, providing continuous, low-intensity forces that enable gradual and more physiological expansion, particularly suitable for pediatric patients or those with limited compliance.

Given the multitude of available devices and protocols, understanding the biological mechanisms, indications, and comparative outcomes of different expansion systems remains essential for optimizing treatment planning and long-term stability.

This narrative review aims to summarize the biological mechanisms and clinical outcomes of rapid maxillary expansion, comparing the efficacy and indications of different expander designs (5).

MATERIALS AND METHODS

A literature search was conducted in PubMed, Scopus, and the Cochrane Library from 2020 to 2025 using combinations of the following keywords: “palatal expander”, “rapid maxillary expansion”, “MARPE), “surgically assisted rapid palatal expansion” and leaf expander”. The search strategy combined the following keywords and MeSH terms: *palatal expander*, *rapid maxillary expansion*, *slow maxillary expansion*, *MARPE*, *surgically assisted rapid palatal expansion*, *Leaf Expander*, *NiTi Expander*, *TSME*, and *fan-type expander*, with a total of 878 articles.

Inclusion criteria

- Human studies published in English.
- Articles investigating the biological basis, mechanical principles, or clinical outcomes of rapid or slow palatal expansion.
- Studies describing different expander designs (tooth-borne, bone-borne, or hybrid) and activation protocols.
- Original research papers, clinical trials, case series, and systematic reviews with adequate methodological descriptions.
- Articles reporting quantitative or qualitative data on skeletal, dentoalveolar, or airway changes.

Exclusion criteria

- Animal studies or *in vitro* experiments.
- Case reports with fewer than three patients.
- Articles not available in English or without accessible full text.
- Studies focusing exclusively on non-orthopedic appliances.
- Duplicated data or secondary publications of the same cohort.

Study selection and evaluation

Two independent reviewers screened the titles and abstracts to exclude irrelevant or duplicate articles. Full texts of potentially eligible papers were then assessed for inclusion based on relevance to the topic and methodological quality.

Data were extracted using a standardized template recording study design and sample size, patient age and skeletal maturity, type of expander used, activation protocol, main skeletal and dentoalveolar outcomes, and follow-up duration.

The methodological quality of included studies was qualitatively evaluated according to criteria adapted from the STROBE (for observational studies) and CONSORT (for clinical trials) checklists, focusing on sample description, intervention clarity, and outcome assessment.

Disagreements between reviewers were resolved by discussion and consensus.

63 studies were included after screening for relevance (Fig.1).

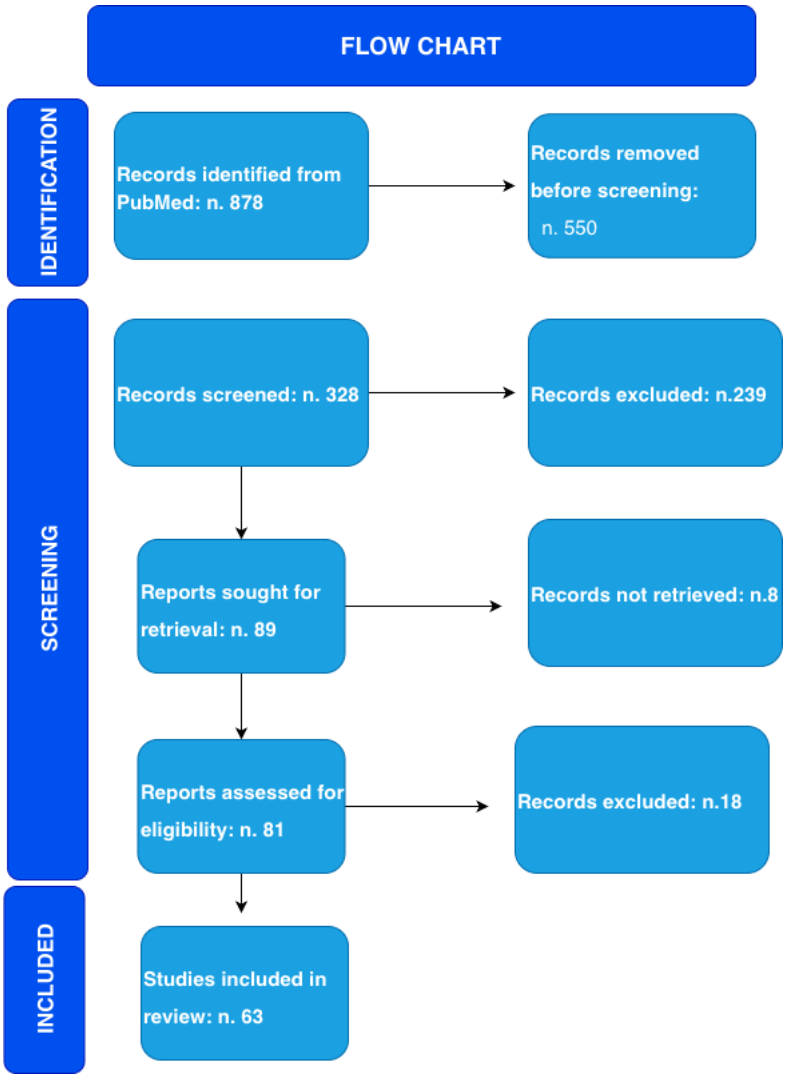

Fig. 1. *Flow chart illustrating the literature selection process according to PRISMA guidelines.*

RESULTS

The analysis of the literature revealed a wide number of articles that had been selected following PRISMA guidelines. The selected literature revealed a variety of techniques, appliance designs and activation protocols, reflecting the continuous evolution of rapid palatal expansion techniques. Each expander type presents distinct biomechanical characteristics, indications, and clinical outcomes, which influence both the skeletal and dentoalveolar responses. The following sections summarize the main categories of rapid palatal expanders currently described in the literature, highlighting their structural features, mechanisms of action, and therapeutic applications.

Biological principles of Rapid and Slow Expansion

Palatal expansion is an orthodontic and orthopedic procedure aimed at increasing the transverse dimension of the maxilla by acting on the midpalatal suture. The biological response to this therapy depends on the magnitude, duration, and rate of the applied forces, which determine whether the resulting changes are primarily skeletal or dentoalveolar (6).

In the case of slow palatal expansion (SPE), in which light and continuous forces are applied, the remodelling of the alveolar bone and supporting structures is gradual, allowing tooth movement through osteoclastic resorption on the pressure side and osteoblastic deposition on the tension side (7). The forces remain within the physiological limits of the PDL, and no significant sutural trauma occurs; This means that SPE leads primarily to dentoalveolar alterations, including buccal inclination of the anchor teeth and alveolar curvature, rather than actual skeletal disjunction (8).

This results in more physiological expansion and less prone to relapse but requires a longer treatment duration.

In rapid palatal expansion, on the other hand, intense, intermittent forces (3–10 kg) are applied for a short period, usually 1–3 weeks. The sudden increase in force compresses the periodontal ligament, leading to temporary hyalinization of the periodontal tissues and interruption of normal tooth movement (9).

Once this occurs, forces are transmitted to the circummaxillary sutures, especially the midpalatine suture, which undergoes rapid mechanical separation. This disjunction triggers an acute inflammatory response followed by osteogenic activity and new bone formation within the cleft (10).

Histologically, three types of biological reactions occur within the bone and connective tissue:

- bioelastic reaction, a temporary deformation that recovers once the load is removed;
- bioplastic reaction, a permanent but adaptive remodelling of the bone matrix;
- biodestructive reaction, associated with microtrauma and subsequent bone resorption when forces exceed physiological thresholds (11).

The midpalatal suture, which remains partially fibrotic until the third decade of life, can respond to mechanical stimuli by activating osteoblast differentiation along the separated sutural margins. During RME, the maxillary halves rotate outward and downward, creating a pyramidal opening with the base located anteriorly and the apex facing the nasal floor (12).

This movement causes an anterior shift of point A, a transient opening of the bite, and mandibular post-rotation, all of which tend to normalize during the retention phase (13).

Histochemical studies have shown that mineral apposition in the suture begins within one month of disjunction, and complete ossification typically occurs within three months (14). Therefore, a retention period of 4–6 months is necessary to allow bone maturation and prevent relapse due to the elastic recoil of surrounding tissues (15,16).

The fundamental biological difference between rapid and slow expansion is, therefore, that in SPE, the forces are low and continuous, affecting the adaptive capacity of the PDL and resulting in primarily dentoalveolar and gradual changes, with minimal trauma.

In rapid expanders, however, the applied forces are intense and intermittent, exceeding the adaptive threshold of the PDL and reaching the sutures. This mechanism produces acute microtrauma, which is then followed by a phase of bone remodelling and new bone deposition through intramembranous ossification (17).

The speed of activation also influences the biological outcome. If the disjunction phase extends beyond 15 days, dental inclination and alveolar curvature begin to prevail, reducing the skeletal effect of the procedure (18).

Conversely, completing expansion within two weeks allows for approximately 80% skeletal enlargement and 20% tooth movement, as reported by clinical and radiographic studies (19).

The response to expansion is highly age dependent. Growing patients exhibit more rapid and stable skeletal changes due to increased cell turnover and reduced suture interdigitation. In contrast, in adults, increased suture interlocking limits expansion, leading to greater dentoalveolar compensation and the need for skeletal anchorage or surgical assistance (20).

In this review, we want to focus more on the types and uses of rapid palatal expansion.

Classification and Clinical Applications

Orthopedic maxillary expansion can be achieved using different activation protocols (slow, semi-rapid, or rapid) depending on the magnitude and frequency of the applied forces (21).

Slow expansion appliances, such as the Quad-Helix or NiTi expanders, apply light, continuous forces (<1 kg) over several months, mainly inducing dentoalveolar changes.

Conversely, rapid palatal expanders generate intermittent heavy forces (3–10 kg) over a short period of 1–3 weeks, resulting in skeletal separation of the midpalatal suture (22,23).

Rapid palatal expanders can be classified into two main groups according to their design and method of activation: (1) Fixed rapid palatal expanders, which are cemented to teeth or skeletal anchorage units; and (2) Removable (mobile) expanders, which are inserted and activated extraorally by the clinician or the patient (24).

Below is an overview of the most clinically relevant devices in both categories.

Fixed Rapid Palatal Expanders

Hyrax Expander

Since its introduction, the Hyrax expander (short for Hygienic Rapid Expander) has been considered the gold standard for fixed, tooth-supported expanders, thanks to its mechanical simplicity, hygienic advantages, and predictable orthopedic effects.

It consists of a central locking screw positioned along the midline of the palate, connected to rigid metal arms welded to orthodontic bands cemented onto the anchoring teeth, usually the first molars and premolars. This

configuration ensures that the expansion forces generated by screw activation are transmitted symmetrically to both halves of the jaw). The absence of an acrylic palatal cover facilitates oral hygiene and prevents fungal colonization, which is more common in acrylic appliances such as Haas (23).

Biomechanically, Hyrax works through intense, intermittent forces, ranging from 3 to 10 kilograms, applied over a short period of time (typically 1–3 weeks). These forces initially compress the periodontal ligament of the anchoring teeth, causing transient ischemia and tissue hyalinization. Only subsequently is the mechanical load transmitted to the circummaxillary sutures, particularly the midpalatal suture. The result is a rapid disjunction of the two maxillary halves, with a pyramidal separation pattern, wider anteriorly and narrower posteriorly, at the level of the nasal floor (25).

Following disjunction, a zone of fibrovascular connective tissue forms between the separated sutural margins, which progressively undergoes intramembranous ossification over the following weeks. During the activation phase, patients typically present with a transient midline diastema between the maxillary central incisors, considered a diagnostic sign of successful sutural opening (19). This diastema tends to close spontaneously within 2–3 weeks due to elastic recoil and transseptal traction of the fibers. The standard activation protocol for the Hyrax expander consists of two daily rotations of 0.25 mm each, achieving an expansion rate of approximately 0.5 mm per day. In most cases, a total expansion of 7–9 mm is achieved within 14 days.

After the active phase, the appliance is passively maintained as a retainer for 3–6 months to allow for bone mineralization and stabilization of the newly formed suture (26).

In growing patients, approximately 70–80% of the expansion is skeletal, with minimal dental tipping (27); whereas in older adolescents and adults, the dentoalveolar components predominate due to increased sutural interdigitation. The Hyrax appliance also has positive effects on nasal airflow and breathing patterns, as the skeletal enlargement of the nasal cavity reduces airway resistance (28).

Haas Appliance

The Haas expander, introduced in the 1960s by Andrew J. Haas, marked a fundamental innovation in the development of rapid palatal expansion techniques (29). Unlike the Hyrax expander, which rests solely on the tooth, the Haas design features an acrylic palatal body that makes close contact with the palatal mucosa. This acrylic component connects the two halves of the pusher screw and extends laterally to span the palatal vault between the posterior teeth, distributing expansion forces both through the anchor teeth and directly to the palatal mucoperiosteum and underlying bone (30).

The acrylic bearings thus transform localized dental loads into broader orthopedic forces, stimulating the periosteum and sutural connective tissue, promoting osteoblastic differentiation, which in turn promotes the apposition of new bone along the separated midpalatal suture. Consequently, the Haas expander produces a greater skeletal effect and a lower rate of tooth tipping than tooth-only expanders such as the Hyrax (30).

The Haas device is able to generate a triangular skeletal separation pattern, with the opening widest anteriorly and tapering posteriorly. This configuration can both correct transverse discrepancies and increase the volume of the nasal cavity, reducing airway resistance (31). The Haas expander is typically activated at a rate of 0.25 mm twice daily for 2–3 weeks, achieving expansion of up to 7–10 mm, depending on the patient's age and skeletal maturity. During activation, patients often experience a midline diastema, indicating suture separation, which then closes spontaneously during the retention period. After completion of active expansion, a retention phase of 4–6 months is essential to allow for osteogenesis and suture consolidation (32).

Despite the many benefits of this device, one issue can be highlighted: the close contact between the acrylic body and the palatal mucosa can lead to hygiene difficulties, mucosal inflammation, halitosis, and temporary speech changes.

Transverse Sagittal Maxillary Expander (TSME)

The Transverse Sagittal Maxillary Expander (TSME), developed by Farronato et al. (33), represents an evolution of traditional rapid palatal expander systems. This device was designed to simultaneously address transverse and anteroposterior maxillary deficiencies, enabling two-dimensional correction.

The TSME consists of three independent expansion screws: a central screw responsible for transverse enlargement and two sagittal screws, one on each hemiarch, for anteroposterior modulation. This configuration allows for differential control of expansion across multiple planes, allowing the clinician to customize the direction, amount, and speed of activation based on the specific skeletal and dental characteristics of each patient (34).

TSME is capable of exerting complex orthopedic forces that act on both the midpalatal suture and the premaxillary region (35). The transverse screw promotes traditional midpalatal separation, while the sagittal screws produce an anterior displacement of the premaxilla, making the device particularly effective in patients with Class III malocclusion, maxillary retrusion, or combined transverse-sagittal discrepancies (36).

CBCT and cephalometric analyses have demonstrated that activation of the TSME allows for a simultaneous increase in the transverse width and sagittal projection of the maxilla, improving skeletal relationships and facial profile. These effects have also been observed to be maintained during the retention phase, indicating good long-term stability and minimal relapse (33). TSME is activated by performing two quarter-turns of the central screw daily for approximately two weeks, followed by weekly activation of the sagittal screws until the desired anterior advancement is achieved. The amount of transverse expansion achieved is comparable to that of conventional RME expanders, while sagittal screws can produce 1–2 mm of anterior movement per side, effectively resolving combined discrepancies (37).

TSME can serve as a preparatory phase for subsequent orthopedic or orthognathic procedures, particularly in borderline Class III patients (38,39).

McNamara (Bonded) Expander

The McNamara expander, also known as the adhesive rapid maxillary expander, is a modified RPE that combines skeletal expansion with vertical control. It was developed to reduce tooth extrusion and bite opening, which are often side effects of traditional tooth-supported expanders.

Unlike Hyrax or Haas appliances, the McNamara design features acrylic bite blocks that cover the occlusal surfaces of the posterior teeth, extending from the premolars to the molars. These resin blocks act as vertical control elements, preventing molar extrusion during activation and promoting counterclockwise mandibular rotation, an effect particularly desirable in patients with a skeletal open bite or a tendency to vertical growth (40).

The acrylic cover redistributes expansion forces along the dental arches and palatal vault, promoting a combination of sutural separation and alveolar remodelling.

The activation protocol is similar to that of conventional RPEs, typically two quarter turns per day (0.25 mm each) for a period of 10–15 days. This is followed by a retention period of 3–6 months, which allows for mineralization of the midpalatal suture (41). The presence of a large acrylic cover can sometimes lead to transient mucosal irritation, phonetic changes, and mild discomfort during the initial adaptation period (42).

Miniscrew-Assisted Rapid Palatal Expansion (MARPE)

In MARPE, or Miniscrew-Assisted Rapid Palatal Expansion, Palatal expansion integrates the mechanical principles of traditional screw jack activation with temporary skeletal anchorage devices (miniscrews), allowing expansion forces to be transferred directly to the maxillary bone rather than the dentition (43).

MARPE devices typically feature four orthodontic miniscrews (two anterior and two posterior) anchored in the paramedian region of the hard palate, where cortical bone thickness is sufficient to ensure stability (44). The miniscrews are connected to a central jack via rigid arms. This configuration allows for uniform distribution of expansion force across the basal bone, minimizing tooth tipping and alveolar flexure, common side effects of conventional ERPs (45). Its design allows MARPE to induce true orthopedic disjunction of the midpalatal suture even in late adolescence and adulthood, where sutural interdigitation has traditionally limited the success of nonsurgical expansion (46). Screw activation allows for localized bone remodelling and recruitment of osteogenic cells along the separated sutural margins, allowing new bone to reform through intramembranous ossification (47).

MARPE has been shown to produce a parallel opening of the midpalatal suture, rather than a triangular one like conventional RME, with greater skeletal expansion at the nasal floor and minimal dental tipping (44). This dynamic is associated with a significant increase in nasal cavity volume and a reduction in airway resistance, which may have positive implications for patients with nasal obstruction or sleep-disordered breathing (48).

The MARPE activation protocol varies depending on the patient's age and skeletal maturity: in adolescents, expansion is typically achieved with 0.25 mm activations twice daily for 14 days, followed by a maintenance period of 3–6 months to allow for bone consolidation (49).

In adults, a slower activation—a quarter turn per day—helps reduce discomfort and allows for more gradual bone adaptation (5).

Systematic reviews and meta-analyses have confirmed that the MARPE technique has high success rates (85-95%) in achieving skeletal expansion without surgery in post-pubertal patients, with failures primarily due to insufficient insertion of miniscrews into the cortical bone or asymmetric activation patterns. Unlike conventional RPEs, which

often produce dentoalveolar changes of 50-60%, MARPE allows for skeletal expansion of up to 80% while maintaining dental inclination within physiological limits (44).

From a patient-centered perspective, MARPE offers the advantages of less discomfort, improved stability, and fewer periodontal side effects, as forces are transmitted directly to the bone rather than through the teeth (50).

Recent research has also explored hybrid designs, such as the bone- and tooth-supported MARPE, which combines skeletal anchorage with limited dental support, particularly suitable for adults with mild sutural resistance (51). Furthermore, long-term follow-up studies confirm that the MARPE produces stable transverse gains with minimal relapse even after 2–3 years, underscoring its reliability as a non-surgical alternative to the SARPE in selected adult cases (52).

Leaf Expander

The Leaf Expander is a device designed to combine the orthopedic effectiveness of conventional RME with greater patient comfort and minimal cooperation requirements.

Its design resembles that of traditional expanders, anchored by bands on the posterior teeth, but instead of a central tightening screw, it features a nickel-titanium (NiTi) leaf spring system, capable of exerting continuous, low-intensity forces of approximately 450–500 grams (53). This device is thus able to deliver a constant force throughout the activation period (54).

The superelastic properties of NiTi alloys allow the expander to generate a constant load, ensuring a constant and biologically compatible stimulus on the midpalatal suture. This condition facilitates bone remodelling and sutural separation, yet without exceeding the periodontal ligament's adaptation threshold. Thus, the risk of hyalinization or microtrauma is significantly reduced compared to screw-based ERPs (55).

Activation of the Leaf Expander is managed by the clinician, as it is pre-set by compressing the spring in the laboratory before cementation. Once positioned, the device releases its force gradually and autonomously, eliminating the need for daily adjustments by the parent; this feature makes this device highly recommended for pediatric patients and/or those with poor compliance (56).

From a biological perspective, it has been demonstrated that, despite the gentler force applied, the skeletal and dentoalveolar effects achieved with the Leaf Expander are comparable to those of traditional Hyrax expanders (57). The midpalatal suture exhibits a similar opening pattern, with a pyramidal configuration that widens anteriorly near the incisor region. Furthermore, the Leaf Expander induces a more physiological bone response, characterized by balanced bone deposition and a reduced risk of root resorption or periodontal stress (56,57).

Clinically, patients report significantly lower levels of pain and discomfort during the activation and retention phases compared to those treated with conventional RPEs due to the continuous, low-intensity force delivery that allows for progressive tissue adaptation and minimal inflammatory response. Furthermore, the Leaf Expander demonstrates stable long-term results in increasing arch width and intermolar spacing, with a reduced tendency for tooth tipping. In mixed dentition cases, it allows for effective orthopedic expansion while maintaining excellent periodontal health (57).

Fan-Type Rapid Maxillary Expander

The Rapid Fan-Shaped Maxillary Expander (F-RME) is a biomechanical refinement of traditional tooth-supported expanders, such as the Hyrax and Haas devices. It allows for selective anterior expansion of the maxillary arch, minimizing posterior widening and buccal tilting of the molars. This makes the F-RME particularly suitable for patients with V-shaped maxillary constriction, anterior crowding, or anterior crossbite, where differential expansion of the dental arch is desirable (58).

Structurally, the F-RME consists of a posterior hinge near the molars and a single anteriorly positioned lifting screw, typically between the first premolars. This configuration allows the two maxillary halves to open in a "fan-like" manner. For this reason, the anterior portion of the palate separates more than the posterior segment, producing an anteriorly dominant expansion pattern (59).

This hinge mechanism allows for the vector of expansion forces to be modified, directing them predominantly toward the anterior region of the maxilla, thus minimizing stress transmission to the zygomatic buttress and the pterygoid junction, which are responsible for skeletal resistance during traditional RPE. For this reason, the F-RME reduces the tendency for buccal tipping of the molars and alveolar flexion, common side effects of other expansion systems (58).

The biological response to forces generated by the F-RME mirrors that of standard RPEs in the anterior palate, although the posterior palate is subjected to less mechanical loading, preserving occlusal stability and reducing vertical

variations. This selective expansion is particularly advantageous in patients with anterior maxillary constriction but normal posterior transverse dimensions, as it allows the clinician to correct crowding or anterior crossbite without overexpanding the molar region (58).

Doruk et al. (2015) observed that, after activation, the F-RME achieved an average intercanine expansion of 4–6 mm, with less than 1 mm of molar movement, demonstrating its accuracy in localized transverse correction.

Another important advantage of the fan-shaped design is the reduction of dental and periodontal side effects; The device is, in fact, able to limit the buccal displacement of the molars and the resulting bone dehiscence or gingival recession (60). This makes the F-RME particularly suitable for patients with thin cortices or reduced alveolar bone thickness in the posterior region.

Several authors have also emphasized the functional benefits of fan-shaped expansion, particularly in improving nasal airflow and tongue posture.

Regarding activation, clinicians generally recommend activations of 0.25 mm twice daily for 10–14 days, achieving a total anterior expansion of approximately 6–8 mm. After active expansion, the device is maintained passively for 3–6 months to allow osteogenesis within the anterior palatal suture and prevent relapse (61).

Surgically Assisted Rapid Palatal Expansion (SARPE)

Surgically assisted rapid palatal expansion (SARPE) is a hybrid orthopedic-surgical procedure designed to overcome the biological limitations of conventional rapid palatal expansion in skeletally mature patients. Indeed, as patients age, their sutures become progressively more interdigitated and mineralized, making nonsurgical expansion unpredictable or even ineffective (62).

The technique involves a Le Fort type I osteotomy, which is then combined with pterygomaxillary disjunction and a midpalatal osteotomy. This controlled surgical weakening of the resistance points allows, with the subsequent application of a screw-type expander such as the Hyrax or Haas, safe and symmetrical separation of the two maxillary halves (63).

From a biomechanical and biological perspective, the SARPE facilitates a cleaner and more parallel opening of the midpalatal suture, which extends posteriorly to the pterygoid plates and the nasal floor. The reduction in skeletal resistance allows the application of lower expansion forces, minimizing tooth tipping, root resorption, and alveolar bone bending (64). The protocol typically involves activation 5–7 days after surgery, with rotations of 0.25 mm twice daily until the desired expansion is achieved (typically 6–10 mm). This is followed by a retention period of 3–6 months to allow for osteogenesis and bone consolidation within the newly formed suture gap.

One of the main advantages of SARPE is the reduction of periodontal and dental side effects associated with conventional RPE in adults (65). Furthermore, the lack of dental anchorage allows for a significant reduction in buccal tipping, alveolar dehiscence, or gingival recession of posterior teeth (64). Additionally, patients often experience improvements in nasal airway volume and respiratory function (66).

Removable (Mobile) Rapid Palatal Expanders

NiTi Palatal Expander (NPE)

The nickel-titanium palatal expander (NPE) leverages the superelastic and shape-memory properties of nickel-titanium alloys to deliver a self-regulating and continuous expansion force of approximately 300–400 grams without manual activation (67).

This constant and gentle force differentiates the NPE from traditional mechanical expanders that rely on screw activation. Thanks to the superelastic NiTi material, even when the appliance deactivates due to arch widening, it can recover its original shape once reinserted, maintaining constant expansion pressure throughout the treatment period (67).

The NPE exerts gentle, continuous forces that remain within physiological limits for the periodontal ligament (PDL) and sutural connective tissues, minimizing tissue hyalinization and promoting constant bone remodelling along the midpalatal suture. The biological response resembles that of slow maxillary expansion (SME) rather than rapid maxillary expansion, with gradual sutural widening and alveolar adaptation rather than abrupt skeletal separation.

Some studies reveal that patient comfort is significantly improved compared to other expanders, with reduced mucosal irritation and greater treatment acceptance. The NPE is particularly suitable for pediatric patients or those with poor compliance, as it does not require daily activation and autonomously exerts controlled expansion forces.

Although NPE therapy has been shown to produce measurable skeletal changes, especially in the anterior palate in early mixed dentition, the extent of skeletal expansion remains less than that achieved with fixed RPEs, underscoring their indication for mild constraints or for post-RPE maintenance.

The total active treatment time averages 8–12 weeks, followed by a maintenance period of 3–4 months to ensure stability.

The main limitations of this device are its inability to correct severe skeletal constraints, its limited control of transverse symmetry in uncooperative patients, and its greater reliance on alveolar flexion rather than true orthopedic widening. For this reason, its best use remains in growing patients, minor constrictions or as a retention phase after Hyrax or Haas expansion.

Removable Acrylic Plate with Expansion Screw

The acrylic plate with midline expansion screw is derived from the classic Schwartz plate. This device consists of a split acrylic base plate, connected by a central locking screw, with retaining clasps attached to the premolars or molars.

When activated, typically with a quarter-turn twice a week, the screw produces gentle, intermittent forces that are transmitted primarily through the teeth and alveolar processes. Consequently, expansion occurs through alveolar remodelling and tooth inclination, rather than through separation of the midpalatal suture, promoting gradual remodelling of the maxillary alveolar bone and controlled widening in patients with mild constriction, dental crowding, or posterior crossbite during the mixed dentition period. Expansion forces, generally less than 1 kg, are well tolerated by young patients and rarely cause discomfort or inflammation (67).

Total expansion typically achieved with this appliance ranges from 3 to 6 mm over a period of 8 to 12 weeks, depending on patient compliance. Because they are removable, treatment success is highly dependent on patient compliance (68).

The main advantages of removable acrylic expanders include ease of use, comfort, and hygiene, while their main disadvantages are compliance-dependent and limited skeletal effectiveness. In adults or late adolescence, their effects are predominantly dentoalveolar and should be considered adjunctive rather than definitive orthopedic interventions.

DISCUSSION

The research surrounding rapid maxillary expansion shows that this method is still a key player in addressing transverse maxillary deficiencies. It can lead to both skeletal and dentoalveolar changes. That said, the biological and clinical results can differ quite a bit based on factors like the patient's age, their skeletal maturity, the design of the appliance, and how the activation protocol is carried out (11,25).

Traditional tooth-borne expanders, such as the Hyrax and Haas appliances, have long demonstrated high clinical efficacy in growing patients. Their orthopedic action promotes midpalatal suture opening and significant skeletal widening, especially when treatment is performed before the pubertal growth spurt. Nonetheless, these devices may also induce undesirable effects, including buccal tipping of anchor teeth, root resorption, and soft tissue inflammation, particularly when forces exceed physiological limits. The Haas appliance, with its palatal acrylic coverage, can achieve a more homogeneous transmission of forces to the palatal vault but requires careful management of oral hygiene to prevent mucosal irritation (30,34).

In contrast, bone-anchored systems, such as Miniscrew-Assisted Rapid Palatal Expansion (MARPE), have revolutionized clinical practice by transferring expansion forces directly to the skeletal structures, thereby minimizing dental side effects. MARPE has proven to be particularly valuable in late adolescents and young adults, where the midpalatal suture becomes more interdigitated and resistant to conventional tooth-borne expansion. Multiple CBCT-based studies have demonstrated that MARPE can achieve parallel sutural separation, greater nasal cavity enlargement, and improved airway function, while maintaining periodontal integrity and long-term stability. However, its success is technique-sensitive and depends strongly on the cortical bone thickness, insertion torque of the miniscrews, and operator expertise. It is also important to underline that most studies on MARPE are limited by small sample sizes and short follow-up periods, making long-term stability uncertain (43,45).

For adults whose skeletal structures are fully developed and where the fusion of sutures makes traditional orthopedic methods ineffective, Surgically Assisted Rapid Palatal Expansion (SARPE) stands out as the top choice. By integrating a Le Fort I osteotomy with mechanical expansion, SARPE guarantees reliable skeletal widening, even suture openings, and minimal dental complications. While it may be more invasive, SARPE offers excellent stability and enhances airway function, especially in cases with significant transverse discrepancies (62).

Recent advancements have brought us NiTi-based expanders, like the Leaf Expander and Nickel-Titanium Palatal Expander (NPE), which deliver continuous, gentle forces (around 450–500 g). These devices mark a significant shift in how we approach expansion, providing gradual forces that are more in tune with the body's physiology, which helps to

lessen pain and inflammation while still promoting effective sutural remodeling. They are especially beneficial for younger patients or those in mixed dentition, as they don't need daily adjustments and provide a steady force (53,55,67).

From a biomechanical standpoint, these innovations reflect a shift from simple mechanical expansion to a more biologically informed orthopedic treatment approach, focusing on how we can guide bone and suture remodeling rather than just separating them. When choosing the right appliance, it's crucial to take into account factors like skeletal maturity, the severity of transverse deficiency, airway function, and the comfort of the patient.

Despite the well-known advantages of RME, there's still a noticeable variation in the outcomes related to skeletal versus dentoalveolar changes. This inconsistency largely stems from differences in study designs, activation rates, and imaging techniques. Plus, we still lack comprehensive long-term data on how stable these results are after retention, especially for newer devices like MARPE and NiTi expanders.

Going forward, research should focus on standardizing activation protocols, creating age-specific treatment guidelines, and using quantitative CBCT and 3D digital models to truly evaluate the skeletal impact of each method. It's also crucial to delve deeper into the biomolecular and histodynamic processes involved in sutural adaptation when mechanical forces are applied, as this could help shape more personalized expansion strategies (57).

The fusion of digital orthodontics, finite element analysis, and hybrid anchorage systems is set to pave the way for the next generation of expanders—devices that will blend mechanical accuracy, biological compatibility, and a design that puts patients first.

In conclusion, while traditional expanders like Hyrax and Haas continue to be dependable options for growing patients, and MARPE has successfully broadened nonsurgical expansion to young adults, the rise of NiTi-based continuous-force devices marks a significant leap toward more natural, comfortable, and tailored treatment approaches.

CONCLUSIONS

Palatal expansion has evolved from a purely mechanical procedure into a biologically guided orthopedic therapy. Rapid maxillary expansion remains the most effective approach to correct transverse maxillary deficiency, promoting true skeletal widening through controlled sutural disjunction.

Appliance selection should be based on the patient's skeletal maturity and clinical needs: Hyrax and Haas expanders are reliable in growing patients, MARPE offers a non-surgical option for young adults, and SARPE remains the gold standard in fully mature cases.

New NiTi-based expanders, such as the Leaf Expander, provide continuous, low-intensity forces that enhance comfort and compliance while maintaining efficacy. Overall, modern palatal expansion integrates orthopedic efficiency, biological compatibility, and patient-centered care, representing a refined, evidence-based strategy in contemporary orthodontics.

Conflict of interest

The authors declare that they have no conflict of interest.

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Review

PEDIATRIC CONDYLAR FRACTURES, A NARRATIVE REVIEW OF THE LITERATURE

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ABSTRACT

Background/Objectives: Pediatric condylar fractures represent a significant percentage of mandibular fractures in children (40%–70%). Early diagnosis and appropriate management are essential due to the potential impact of these fractures on mandibular growth and the risk of complications, including temporomandibular joint (TMJ) ankylosis. Despite extensive literature, therapeutic options, ranging from conservative management to closed or open surgical approaches, are still debated. This narrative review examines the etiopathogenesis, diagnosis and available treatment strategies to support evidence-based management of pediatric condylar fractures. *Methods*: A database search was conducted through PubMed, Embase and Scopus using specific MeSH terms and Boolean operators. Included studies focused on pediatric patients with unilateral or bilateral condylar fractures, published between 2015 and 2025 in English. *Results*: Among the retrieved records, 22 articles met the inclusion criteria and were qualitatively analyzed. Pediatric mandibular condylar fractures (PMCFs) mostly affect children aged 5 to 12 years and are commonly caused by falls and road traffic trauma. CT and CBCT demonstrated superior diagnostic accuracy compared to panoramic radiography, particularly in assessing the degree of displacement and mandibular ramus height. Owing to the natural condylar remodeling capacity and the ability to maintain mandibular symmetry during growth, conservative treatment has shown excellent functional and morphological outcomes. Additional therapeutic options include open or closed surgical approaches and recently introduced minimally invasive techniques. *Conclusions*: Conservative treatment remains the first-line approach, ensuring effective functional recovery and preservation of mandibular symmetry through natural remodeling. Surgical intervention is reserved for more complex cases in which severe displacement would otherwise prevent adequate healing. Among the available management techniques, newer minimally invasive procedures such as external fixation have emerged as promising alternatives, although their use remains limited to specific indications.

KEYWORDS: *Pediatric condylar fractures, temporomandibular joint, orthodontic therapy, maxillofacial surgery, mandibular fractures*

INTRODUCTION

Mandibular fractures are among the most common maxillofacial fractures in children; within this group, condylar fractures account for 21% to 72% of cases (1), with a peak incidence between 5 and 8 years of age. Considering that the mandible reaches its final dimensions at approximately 14 to 16 years in girls and 18 to 20 years in boys (2), condylar trauma is of particular relevance in the growing child. The most common complications include mandibular growth

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disturbances and temporomandibular joint ankylosis. Fractures in children under five years of age are uncommon and are mainly caused by falls; additional etiologies include road traffic accidents, sports injuries, and assaults (3).

Given the central role of the condyle in mandibular development, understanding craniofacial growth mechanisms is essential for interpreting both the behavior of condylar fractures and their long-term effects.

As highlighted by Manlove et al, craniofacial growth results from the interaction between genetic factors, functional influences, and specific growth centers such as the mandibular condyle. Two types of cartilage contribute to early craniofacial growth. Primary cartilage is genetically driven, grows interstitially, is pressure-tolerant, and avascular. In contrast, secondary cartilage, including the cartilage of the condylar head, coronoid process, mandibular angle, and mental protuberance, is not primarily genetically regulated. Instead, it is highly adaptive, responding to functional stimuli and environmental influences (4).

This characteristic makes the mandibular condyle particularly vulnerable to trauma in the growing child, and it can lead to important complications such as mandibular growth disturbances and temporomandibular joint ankylosis (5).

Fractures in children under five years of age are uncommon and are mainly caused by falls; additional etiologies include road traffic accidents, sports injuries, and assaults (6).

Early diagnosis is crucial: it has been consistently reported that undiagnosed or untreated condylar fractures may lead to significant functional consequences. As noted by Lee et al. (7), a clear association exists between injury to the cartilaginous portion of the condylar head and subsequent facial growth disturbances. These complications may later necessitate orthognathic or temporomandibular joint surgery and may result in permanent joint dysfunction.

A study conducted by E. Chacón et al. compared two imaging techniques, panoramic radiography (OPT) and computed tomography (CT), to determine which was more effective for diagnosing condylar fractures. Their findings demonstrated that CT has superior sensitivity, specificity, and diagnostic accuracy compared to OPT, which showed a high incidence of false negatives and false positives (8).

Pediatric condylar fractures may result in mandibular asymmetry, occlusal alterations, and changes in facial aesthetics, given the involvement of an active growth center (9,10).

The choice between surgical and conservative management remains a subject of considerable debate. Condylar remodeling and adaptive changes are well documented in patients treated non-surgically, which is why most authors recommend conservative treatment as the first-line approach in children (11,12).

The objective of this narrative review is to provide a comprehensive overview of the etiology, diagnostic approaches, and treatment modalities of pediatric condylar fractures. Given their high frequency, clinical relevance and the current absence of a standardized management protocol, this review aims to summarize the main fracture patterns, assess their prevalence, and outline the most up-to-date strategies currently adopted in clinical practice for their evaluation and management.

MATERIAL AND METHODS

A narrative review was conducted following a structured search strategy inspired by PRISMA guidelines, consulting PubMed, Embase and Scopus databases. All studies published between 2015 and 2025 and involving patients younger than eighteen years, with unilateral or bilateral condylar fractures and an assessment of clinical or radiological outcomes, were included.

Studies with fewer than five patients, animal studies, in vitro investigations, reviews, and cohorts exclusively involving adults were excluded. Relevant reference textbooks (Proffit, Okeson) were also consulted.

Inclusion criteria

Studies were included if they met the following criteria:

- human subjects younger than eighteen years;
- unilateral or bilateral condylar fractures;
- assessment of clinical or radiological outcomes;
- publication in English;
- original studies, including prospective or retrospective cohorts and case series with at least five patients.

Exclusion criteria

- case reports or studies with fewer than five patients;
- animal studies;
- *in vitro* studies;

- narrative or systematic reviews;
- studies exclusively involving adults.

The search queries used for the database screening are listed in Table I (Table I).

Table I. *Overview of the three databases and the search strategies used.*

PUBMED	SCOPUS	EMBASE
("Mandibular Condyle"[MeSH Terms] OR "mandibular condyle" OR "condylar process" OR "temporo-mandibular joint condyle" OR "mandibular fractures"[MeSH Terms]) AND ("Fractures, Bone"[MeSH Terms] OR fracture* OR break*) AND ("Child"[MeSH Terms] OR "Adolescent"[MeSH Terms] OR pediatric OR paediatric OR child* OR adolescen* OR "young patient" OR "growing patient" OR "growth phase" OR "growth period" OR "developing patient") NOT ("Adult"[MeSH Terms] OR adult* OR elderly OR aged OR "grown-up")	("mandibular condyle fracture" OR "fracture of the mandibular condyle" OR "condylar fracture of the mandible" OR "mandibular condylar fracture") AND (child OR children OR adolescent OR pediatric OR paediatric) AND NOT (adult OR "adult patient" OR "grown up" OR elderly OR aged) AND NOT ("femoral condyle" OR "humeral condyle" OR "tibial condyle")	('mandibular condyle'/exp OR 'mandibular condyle' OR 'condylar process' OR 'temporo-mandibular joint condyle' OR 'mandibular fracture'/exp OR 'mandibular fractures') AND ('bone fracture'/exp OR fracture* OR break*) AND ('child'/exp OR 'adolescent'/exp OR pediatric OR paediatric OR child* OR adolescen* OR 'young patient' OR 'growing patient' OR 'growth phase' OR 'growth period' OR 'developing patient') NOT ('adult'/exp OR adult* OR elderly OR aged OR 'grown-up') NOT ('femoral condyle' OR 'humeral condyle' OR 'tibial condyle')

After screening all the articles, twenty-two studies were included in the qualitative synthesis (Fig.1). Table II shows the characteristics of the studies included in the review (Table II).

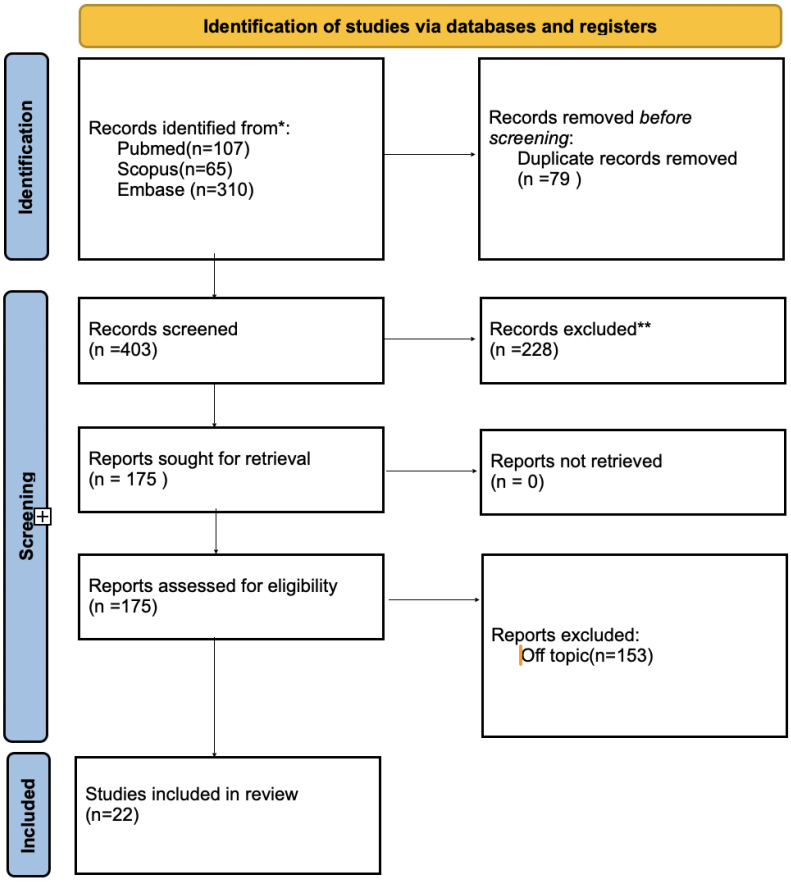

Fig. 1. *PRISMA 2020 flow diagram showing the literature search and study selection process leading to the inclusion of 22 studies.*

Table II. *Characteristics of the studies included in the review (n = 11): title, sample, authors, aim, results and type of study.*

TITLE	SAMPLE	AUTHORS	AIM	RESULTS	TYPE OF STUDY
Epidemiological Study of Pediatric Mandibular Condylar Fractures	186 pediatric patients with uni or bi lateral fracture	Award NM;Sabry HA; Elhadidy MS	Epidemiological analysis and outcomes of management:charactestics,conservative and long term results of mandibular fracture.	Condylar fractures represent 67% of pediatric mandibular injuries; 72% are unilateral. 59,5% was managed conservatively with good function.	Retrospective study
Long-term follow-up of mandibular condylar fractures in children	42 children <18 years 23 M e 19 F with 54 condylar fracture	Lekven N;Neppelberg E; Tornes K	Long term evaluation of clinic and radiographic non surgical treatment	Unilateral fractures showed more unfavorable results than bilateral fractures. Radiologic examination showed in: 87% -9% and 4% complete moderate and poor remodeling	Prospective cohort study
Prospective Evaluation of Closed vs Open Treatment in Children	24 patients<14 years	Landes CA;Day K; Glasl b; Ludwig b Sader R;Kovacs AF	Evaluation of long-term outcomes following open reduction for displaced pediatric condylar fractures versus closed management of non-displaced cases.	Closed treatment resulted in good function and full range of motion, while ORIF improved anatomical alignment but did not show clearly superior long-term outcomes.	Retrospective epidemiological study
A comparative study of 2 imaging techniques for diagnosis	22 males and 15 females (ages ranging from 2 to 15 years)	Chacon GE;Dawson KH; Myall RWT; Beirne OR	Compare the sensitivity and specificity of panoramic radiographs with those of coronal computed tomography (CT) scans in the diagnosis of mandibular condylar fractures	CT scans provide greater accuracy of diagnosis, sensitivity and specificity than panoramic radiographs. Coronal ct should be a routine investigation	Comparative diagnostic study
Serious Condylar Head Absorption in Children Treated Operatively with Long Screws	Children (less than 12 y old) who sustained intracapsular condylar fractures and fixed with long screws	Jun-Yi Xu;Hai-Hua Zhou;Kun Lv; Rong-Tao Yang; Zhi Li;Zu-Bing Li	Explore bone remodeling in children with intracapsular condylar fractures after the condylar fracture fragments were fixed using long screws and explains the underlying mechanism.	Intracapsular condyle fractures in children should be managed conservatively unless the height of the fracture fragments drops remarkably,. In this case open reduction and rigid internal fixation become possible choices.	Case series
Fracture fragment determines ramus height (intracapsular fractures)	children < 12 years with intracapsular fractures.	Rui-cong Yang;Meng-juan Cui;Hai-hua Zhou;Kun Lv;Rong - Tao Yang;Zhi Li;Zu-Bing Li	Explore and understand bone remodeling in children with intracapsular fractures treated conservatively	In 22 children, conservative treatment led to healing in the displaced position with no spontaneous reduction. Remodeling occurred mainly through horizontal/mixed resorption, and ramus height depended on the displaced fragment. Significant height loss may require ORIF.	Observational study
Does closed treatment result in restitutional remodeling?	41 patients with 57 fractures	Yadav P;Bhutia O;Bansal A;Lakshmanan S; Roychoudhury A	the aim of this study was to assess whether non-operative management of pediatric mandibular condylar fractures allows the condyle to regenerate with a restored, normal morphology following closed treatment (restitutional remodeling)	In all patients fractures remodeled to normal morphology after non-operative treatment, with improved mouth opening, good occlusion, and no asymmetry or TMJ ankylosis.	Retrospective study
Radiographic 3D evaluation of condylar fractures after closed treatment	96 patients with 142 condylar fracture sites	Du C; Xu B; Zhu Y; Zhu M	Investigating a new three-dimensional classification of healing morphology in condylar fractures in children and adolescents after closed treatment, and establish its association with fracture type and clinical outcomes	The purpose of the article was to investigate a new three-dimensional classification of condylar healing morphology in children and adolescents after closed treatment, and to determine whether these healing patterns are associated with fracture type and clinical outcomes.	Prospective study
Comparison of open reduction vs closed treatment in pediatric mandible fracture	77 pediatric patients (age <12 years) with 100 fractures	Bansal A;Yadav p;Bhutia O;Roychoudhury A;Bhalla AS	Compare outcomes and complications between open reduction and internal fixation (ORIF) and closed treatment in pediatric mandibular fractures	All patients achieved bone healing. Maximal incisal opening was comparable between closed treatment and ORIF, with no significant difference.	Retrospective and comparative study
Dislocated pediatric condyle fractures - should	Children with dislocated condyle fractures	Vesnaver A	Present and analyze the results of surgical treatment	Surgical treatment of dislocated (luxation-type) condylar fractures in children and infants restores the	Retrospective comparative study

conservative treatment always be the rule?				anatomy and reliably enables symmetric growth of the condyles, mandible, and facial skeleton.	
Three-dimensional evaluation of condylar morphology after closed treatment	31 participants	Zhu Y.F ;Zou Y;Wang SZ;Du CX; Xu B;Zhu M	Investigate the condylar morphology after closed treatment of unilateral intracapsular condylar fracture in children and adolescents through three-dimensional evaluation and explore the influence of age, type of fracture, treatment methods and concomitant fracture on the treatment effectiveness	Children had great growth potential to compensate the shortening of condylar process after intracapsular condylar fracture, so closed treatment could be an effective therapy for or young children and adolescents	Retrospective study
Management of Pediatric Condyle Fractures – retrospective review	44 patients with 49 condyle fractures	McGoldrick D ;Parmar P; Williams R;Monaghan A; McMillan K	Examine the demographics, etiology, treatment, and outcomes of condylar fractures managed in a single pediatric trauma unit.	Conservative management in isolated fractures resulted in stable outcomes and this large case series supports the consensus that management of pediatric condyle fractures should be as conservative as possible.	Retrospective review
Mandibular Condylar Fractures in Children – Results after External Fixation	21 pediatric patients, 13 girls and 8 boys<18 years	Cascone P;Marcozzi MM;Ramieri V;Bosco G;Vellone V; Spallaccia F	Evaluate the long-term outcomes of paediatric patients treated surgically with external fixation	Surgical approach using external fixation could be considered an option for treatment of mandibular condylar fractures in paediatric patient. Vertical height recovery, early mobilization, and good occlusion can be achieved, minimizing the risk of facial asymmetry.	Case series
Nonsurgical management of condylar fractures in children – 15-year study	84 patients (mean age: 8.9 years) with 106 condylar fracture sites	Theologie-Lygidakis N;Chatzidimitriou K;Tzerbos F;Gouzioti A; Iatrou I	To present the 15 years of experience after closed treatment of condylar fractures in children, by evaluating the short- and long-term results and propose treatment modalities	conservative treatment of condylar fractures is the treatment of choice in children.The child's age, adequacy of function of the mandible, degree of displacement or or dislocation of the condylar fragment, and need for active kinesiotherapy should be considered in all cases.	Retrospective study
Open reduction and internal fixation obtains favorable outcomes	9 children diagnosed with MCF and treated surgically with ORIF.	Zhang L;Wang Y;Shao X;Chen J	Evaluate the clinical and radiographic outcomes of the children with MCF treated surgically with ORIF.	ORIF for displaced fractures restored joint function rapidly; no significant growth alteration at follow-up.	retrospective cohort study
Restoration of ramus height in extracapsular fractures	35 children <12 years old with extracapsular condylar fractures	Zhou HH;LV K;Yang RT;Li Z; Li ZB	Assess whether ramus height is restored in children with extracapsular condylar fractures treated by conservative or surgery procedures.	Conservative treatment could hardly restore the ramus height of children with extracapsular condylar fractures. Anatomically or totally restoring the ramus height is difficult even with the surgical treatment of ORIF but it can substantially restore the ramus height for dislocated fractures or seriously displaced fractures.	Retrospective study
Classification and treatment strategies for condylar fractures in children	84 patients with 123 condylar fractures	Li M-X; Xing X; Li Z B ;Li Z	Describe a classification method and the corresponding treatment strategies for condylar fractures in children, based on the anatomical position and displacement of the fracture	This new classification improved treatment planning; alignment with outcome consistency.	Retrospective study
Transoral endoscopic assisted reduction and internal fixation of mandibular condylar fractures in children retrospective case series	12 patients with 14 condylar fractures between the ages of 3 to 11 years.	Abdelazeem M H ;Aboelela S ;Erdogan O	Evaluate the outcomes of transoral endoscopic assisted open reduction and internal fixation of condylar fractures and hardware removal in pediatric patients	The transoral approach is a reliable technique for reduction and internal fixation of condylar fracture. The serious risks of extra oral approaches (facial nerve injury ,facial scar can be eliminated	Retrospective case series
Non invasive management of pediatric isolated condylar fractures: less is more	43 patients with 50 mandibular condylar fractures	Joseph Lopez; Isabel V Lake;Nima Khavanin; Bartlomiej Kachniarz; Omar Najjar; Navid Pourtaheri;Richard J Redett;Paul N Manson;Amir H Dorafshar	The purpose of this study was to examine injury patterns in pediatric mandibular condylar fractures and to propose and evaluate the validity of an institutional treatment .	Non operative management has a low complication rate in deciduous dentition. Children with permanent/mixed dentition may undergo closed treatment and mandibulomaxillary fixation if they have malocclusion,contralateral open bite,	retrospetive cohort study

				significant condylar dislocation, and ramus height loss greater than 2 mm.	
Aduction of the condyle had leads to condylar resorption: a radiologic study in children with intracapsular fractures	93 children with 104 condylar head fractures	Hai-Hua-Zhou;Kun LV; Rong Tao Yang; Zhi Li; Xue-Wen Yang; Zu Bing Li	This study aimed to explore and understand if absorption existed in children with intracapsular fractures.	Post-treatment condylar abduction is closely linked to condylar resorption, especially when pediatric fractures occur near the medial condylar region. Both surgery and conservative approaches fail to effectively correct this abduction.	retrospective observational study
Treatment of pediatric Condylar Fractures: A 20-Year Experience	64 patients with 92 condylar fractures were identified	Ghasemzadeh, Ali B.S.; Mundinger, Gerhard S. M.D.; Swanson, Edward W. M.D.; Utria, Alan F. B.A.; Dorafshar, Amir H. M.B.Ch.B.	The purpose of this study was to define patterns of injury and treatment for condylar and subcondylar fractures and evaluate short-term outcomes in the pediatric. patients	Conservative treatment yields optimal results in pediatric patients.If condylar fractures are combined with additional arch fractures experience a higher rate of unfavorable outcomes	retrospective observational study
Outcomes of functional treatment of condylar mandibular fractures with an articular impact: a retrospective study of 108 children	Young patients (< 15 years of age) presenting unilateral or bilateral mandibular fracture of the condylar process	Maling M; Grimaud F; Perrin J P ;Loin J; Anquetil M; Mercier J ;Corre P; Bertin H	assess the long-term clinical and radiographic outcomes of functional treatments for mandibular condylar fractures with an articular impact.	Functional treatment of mandibular condylar process fractures in children generally leads to satisfactory long-term functional and architectural outcomes. Early mobilization of the injured joint and long-term follow-up of children until they have completed their growth are key to obtaining optimal outcomes.	retrospective study

RESULTS

Across the 22 included studies, pediatric condylar fractures emerged as the most frequent type of mandibular fracture, with unilateral involvement being the predominant pattern (67%). The most reported causes were falls and road traffic accidents (13,14).

Evidence from the comparative diagnostic study by Chacón et al. demonstrated that CT/CBCT provides superior diagnostic accuracy compared with panoramic radiography, particularly in detecting condylar displacement and assessing ramus height discrepancies (8).

Most studies conclude that conservative management represents the first-line approach for the majority of pediatric condylar fractures. This preference is supported by the high remodeling capacity of the pediatric condyle, which enables excellent functional recovery, stable occlusion, and maintenance of mandibular symmetry (1,14-16).

Several cohorts documented complete or substantial morphologic remodeling, especially in children under six years of age, whereas older children showed partial adaptive remodeling, often compensated by modifications of the glenoid fossa or ramus height (17–19).

Closed treatment, ranging from soft diet and early mobilization to guiding elastics or short-term maxillomandibular fixation, achieved functional outcomes comparable to surgical management, with satisfactory improvements in mouth opening and occlusal stability (20–22).

Surgical approaches, including open reduction and internal fixation (ORIF), external fixation, and transoral endoscopic-assisted reduction, were reserved for severely displaced, luxated, or combined fractures. These techniques were effective in restoring anatomical alignment but carried higher risks of postoperative condylar resorption, limited remodeling, and potential growth disturbances, particularly in intracapsular fractures treated with long screws (2,23–25).

External fixation (24) and transoral endoscopic-assisted ORIF (25) have shown favorable functional outcomes in pediatric mandibular condylar fractures, with reduced morbidity and the advantage of avoiding facial scarring.

Cephalometric evidence, such as that reported by Farronato et al., shows that the growing mandible undergoes sagittal and rotational adaptations in response to orthopedic stimuli originating from the maxilla. The observation of these structural compensatory mechanisms reinforces the concept that the pediatric condyle, thanks to its high remodeling capacity, can recover shape and function when appropriately guided, as advocated by contemporary management protocols for condylar fractures (26).

Overall, the collective evidence consistently highlights the predominance of conservative treatment, the importance of early mobilization, and the exceptional remodeling potential of the pediatric condyle as key determinants of favorable long-term outcomes.

DISCUSSION

Age and fractures

Pediatric condylar fractures result from direct trauma or the transmission of forces along the mandibular arch and may lead to malocclusion, mandibular asymmetry and growth disturbances. The incidence and type of fracture vary significantly with age: intracapsular fractures are more common in children under seven years, because the mandibular neck is shorter and structurally more robust, whereas fractures of the neck and base become more frequent after the age of seven as the condylar region elongates and becomes thinner (16). This distinction is clinically relevant, as intracapsular fractures directly involve the condylar head and may therefore affect the growth center more severely, while extracapsular fractures primarily influence the vertical stability of the mandibular ramus.

Management

Management strategies for pediatric condylar fractures are generally divided into operative (closed or open) and non-operative approaches. The main objective of any treatments protocol is to restore mandibular function and symmetry while preventing malocclusion or mandibular dysfunction. A widely referenced protocol was proposed by Banks (27), who outlined treatment recommendations based on age and fracture site:

- Condylar head, neck, and base fractures in children younger than five years should be treated with closed or functional therapy for two weeks;
- Condylar head fractures in children older than five years also require closed or functional treatment for two to four weeks;
- In condylar neck and base fractures occurring between five and eight years of age, open reduction is recommended as the first choice.

If open reduction is not feasible, the recommended sequence includes three to six weeks of intermaxillary fixation, followed by four weeks of functional therapy, and three months of clinical monitoring.

Non-operative management consists of a liquid diet, physiotherapy exercises, and anti-inflammatory medications, which may be combined with functional appliances. Close monitoring of maximal mouth opening is essential. This approach is particularly indicated for condylar head fractures without marked deformity. Conservative treatment relies on the natural remodeling capacity of the condyle, allowing both morphological and functional recovery (19). Early mobilization also helps prevent TMJ ankylosis and promotes bone regeneration following Wolff's law. Three-dimensional studies, such as the one conducted by Du et al., demonstrated that the condyle can heal with a morphology that is not perfectly anatomical without compromising function, reinforcing the rationale for closed treatment in many children (17).

According to a study conducted by Smith et al., bilateral fractures with reduced mandibular height, premature posterior contact, and an open bite require a more aggressive treatment approach, which includes:

- A brief period of maxillomandibular fixation (MMF) in younger children, using creative methods,such as circummandibular wiring and piriform drop wires,to avoid damaging developing tooth buds;
- ORIF combined with MMF in older children;
- Displaced unilateral condylar neck fractures can often be managed with closed reduction, arch bars, and contralateral vertical elastics.

When bone fixation is required, the risk of injury to developing tooth germs can be minimized by using monocortical screws and positioning the hardware along the inferior border of the mandible. Resorbable hardware may also be used, and metallic plates can be removed once adequate healing has occurred.

After 11 years of age (or 8 years for symphysis fractures), bicortical screws or transosseous wires may be employed (28-29).

Remodeling capacity is a crucial parameter in the therapeutic decision-making process. It is highest in children under six years, moderate between six and twelve years (the "gray zone"), and progressively decreases after twelve years. The literature shows that most unilateral fractures in younger children evolve favorably with conservative management because of the notable plasticity of the condyle, which can restore both form and function even with considerable displacement. However, radiologic outcomes may occasionally be less satisfactory, particularly when a reduction in ramus height occurs, which may predispose to long-term asymmetry (18).

Zhu et al. investigated condylar morphology following closed treatment in growing patients and reported restitutio ad integrum in children under six years. In patients older than six years, healing occurred with shortening and thickening of the fractured condylar process. Nonetheless, the shorter condyle was compensated by thickening of the glenoid fossa and an increase in ramus height, maintaining the pogonion at the midline and preserving symmetry and function (30).

In addition to remodeling potential, the degree of displacement must be carefully evaluated. In cases of displacement greater than 45 degrees, significant loss of ramus height, or dislocation of the condylar head from the glenoid fossa, conservative treatment alone is insufficient and alternative therapeutic strategies must be considered.

Closed management, categorized as operative treatment, consists of intermaxillary fixation (MMF) using arch bars or orthodontic brackets for approximately fourteen days. In some situations, MMF is combined with functional therapy using elastics. However, several authors have questioned the benefit-risk ratio of MMF, supporting early mobilization to improve lymphatic and vascular circulation around the fracture site and accelerating condylar regeneration (31).

Open reduction and internal fixation (ORIF) are indicated primarily in severely displaced fractures, in cases with marked ramus height loss, in combined injuries such as symphyseal–condylar fractures, and in adolescents nearing skeletal maturity where remodeling capacity is limited and spontaneous realignment is less likely (18).

Despite its usefulness, ORIF is reserved for a minority of cases, as the placement of plates and screws may compromise condylar vascularization and increase the risk of postoperative resorption, and often requires a second surgery to remove the hardware to prevent interference with mandibular growth (32,33).

An additional insight into functional treatment is given by the study of Malinge et al; that reinforces the role of functional therapy as an effective and biological approach for a lot of pediatric fractures. The study included 108 patients, 33 of whom were followed until growth completion. Their protocol, based on early mobilization of the fractured condyle through propulsion and diduction, supported by elastics, nighttime neutral fixation, and physiotherapy, resulted in rapid recovery of mandibular movements and normalization of function at the end of growth, with no differences between unilateral and bilateral fractures. Despite the favorable functional outcomes, 27.3% of patients developed TMD in adulthood, particularly after unilateral fractures, although the causal relationship remains uncertain. Mild forms of posterior vertical insufficiency (PVI) were noted in a subset of patients; however, compensatory remodeling of the condyle and glenoid fossa often minimized clinical asymmetry. Remodeling capacity was highest in younger children and decreased with age (34).

Furthermore, intra-articular soft tissue involvement must be considered: the trauma responsible for the fracture may injure the articular disc or ligaments, which lack regenerative capacity. Failure to reduce the disc may lead over time to pain, joint noises, restricted mouth opening, and altered mandibular growth. For these reasons, the degree of displacement is one of the most important determinants in guiding treatment selection (35).

Neither conservative management nor ORIF can fully restore ramus height in extracapsular condylar fractures. As demonstrated in the study by Zhou et al., surgical treatment is more effective in cases with severe dislocation; however, residual deformities may still persist. Therefore, the choice of treatment should depend on the type of fracture and on an accurate assessment of the potential impact on mandibular growth. A prolonged follow-up period and an individualized treatment approach are essential (36).

To minimize the impact on condylar growth, external fixation has recently been introduced as an alternative technique. It allows stabilization of the fracture fragments while avoiding direct interference with the condyle and permits atraumatic device removal, as shown by Cascone et al. (24).

Similarly, the introduction of transoral endoscopic-assisted ORIF (TEA-ORIF) has expanded therapeutic options for severely displaced fractures by enabling precise anatomical reduction with minimal morbidity, no external scarring, and a reduced risk of facial nerve injury. Early evidence indicates promising functional and morphological outcomes, although larger prospective studies are needed before definitive comparisons can be established with traditional techniques (25).

Dental development also influences treatment choice. In mixed dentition, decisions must be individualized. In permanent dentition, severe displacement often requires closed treatment supported by ORIF. Combined symphyseal–condylar fractures carry a higher risk of condylar displacement and postoperative complications due to their biomechanical instability. Another unfavorable prognostic factor is lateral condylar abduction, commonly seen in pediatric intracapsular fractures; it is a predictor of post-traumatic resorption and is not effectively corrected by either closed treatment or ORIF (37).

In recent years, new classification systems have been proposed to improve treatment planning and reduce variability in clinical decision-making. Among these, the PD Classification introduced by Li M X et al. (38) stands out as a comprehensive framework specifically designed for pediatric condylar fractures. It integrates the anatomical location of the fracture (P: condylar head, neck, or base) with the degree of displacement (D1 to D5, from minimal displacement to complete dislocation). According to this model, P1 to P3 fractures with mild or moderate displacement (D1 to D3) are generally suitable for conservative treatment because of the high remodeling potential in children. Conversely, fractures of the neck or base with severe displacement or full dislocation (D4 to D5) are more likely to benefit from surgical reduction to prevent persistent ramus height loss or long-term asymmetry. Although broader validation is still needed, the

PD Classification provides a promising tool to standardize indications and guiding clinicians in distinguishing cases appropriate for conservative management from those requiring operative intervention.

Overall, available evidence confirms that closed treatment remains the safest and most effective strategy for the majority of pediatric patients. The most frequent complications, such as malocclusion or mild asymmetry, are primarily seen in cases where condylar fractures are associated with mandibular arch fractures, while isolated condylar fractures generally result in more favorable outcomes.

CONCLUSIONS

At present, no universally accepted guidelines to determine the most appropriate treatment for pediatric condylar fractures across different age groups are available.

Condylar fractures in childhood occur frequently, often with minimal pain and discomfort and therefore the diagnosis is not made at the time of injury (39).

Furthermore, the literature shows that Class II malocclusion, even the second division, is not a primary cause of TMD, which has a multifactorial origin. This reinforces the idea that, in pediatric condylar fractures, the development of joint symptoms cannot be attributed solely to occlusal factors but rather to a combination of growth, functional adaptation, and trauma-related mechanisms (40-43).

Therapeutic decisions therefore rely on individualized assessment and shared decision-making between clinicians, patients, and family (44-48).

Based on the evidence, conservative management remains the preferred option for most children under twelve years of age, owing to their substantial condylar remodeling capacity. However, uncertainties persist regarding the precise indications for surgery and the balance between growth preservation, functional recovery, and the risk of complications (49-52).

Surgical treatment is reserved for patients in whom spontaneous recovery is unlikely, such as severe dislocations, significant loss of ramus height, combined fractures, or adolescents approaching skeletal maturity. Minimally invasive techniques, including TEA-ORIF and external fixation, represent emerging alternatives with encouraging preliminary outcomes (53-55).

The overall quality of evidence remains limited by retrospective designs and small case series. Well-designed prospective studies are needed to more accurately define surgical indications and to optimize management strategies for these fractures.

Finally, long-term clinical and radiological follow-up is essential, as late remodeling alterations may appear years after trauma and potentially affect mandibular growth.

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Conflict of interest

The authors declare that they have no conflict of interest.

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Comparative Study

ITALIAN SCHOOL-BASED ORAL HYGIENE EDUCATION: A COMPARISON BETWEEN TRADITIONAL TEACHING METHODS AND THE MONTESSORI APPROACH

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ABSTRACT

Background: Oral health education during childhood is essential for establishing long-term preventive behaviors. Traditional school-based programs often rely on passive teaching strategies, which may limit children's engagement. Child-centered and multisensory approaches, such as the Montessori method, may enhance learning by promoting active participation, autonomy, and emotional involvement. This study compared a traditional oral hygiene education program with a Montessori-based intervention in children aged 7–9 years, focusing on cognitive, behavioral, and emotional outcomes. *Methods:* Thirty-six children from an Italian primary school were equally allocated to a traditional education group or a Montessori-based experiential learning group. A pre–post study design was used to assess oral health knowledge, brushing habits, attitudes toward dental care, and emotional responses, the latter evaluated through drawing analysis. *Results:* Both groups showed improvements following the interventions; however, the Montessori group demonstrated greater gains in oral health knowledge, twice-daily toothbrushing, adoption of the modified Bass technique, positive attitudes toward dental visits, and reduced dental anxiety. Drawing analysis revealed higher levels of emotional comfort and engagement in the Montessori group. *Conclusions:* Montessori-based oral hygiene education appears to be more effective than traditional methods in promoting preventive behaviors and positive emotional experiences, supporting its integration into school-based oral health programs.

KEYWORDS: *Oral hygiene, preventive dentistry, Montessori method, pediatric dentistry, comparative study*

INTRODUCTION

Oral health represents a fundamental component of quality of life in childhood, exerting a significant influence not only on children's physical well-being but also on their psychological, social, and academic development (1). Compromised oral health can interfere with nutrition, speech, participation in social activities, self-esteem, and school performance. Despite advances in preventive and therapeutic dentistry, untreated dental caries remains one of the most prevalent chronic diseases in children worldwide and is frequently associated with inadequate oral hygiene practices and unhealthy dietary habits (2).

The scientific literature widely recognizes early prevention as the most effective and economically sustainable approach to controlling oral diseases, compared to restorative dental treatment later in life (3,4). From this perspective, it is essential to promote preventive and oral health education programs targeting not only children but also their parents,

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who play a crucial role in establishing and maintaining appropriate oral hygiene and dietary behaviors. Family engagement and awareness can significantly reduce the incidence of caries-related conditions and promote the adoption of protective behaviors from early childhood (5).

Schools represent an ideal setting for implementing structured oral health education interventions, as they allow for systematic, continuous, and large-scale dissemination of preventive messages (6).

Orthodontic literature has highlighted how early interventions may influence not only dental occlusion, but also functional aspects such as breathing patterns and craniofacial growth (7,8). These findings underline the importance of preventive strategies and patient cooperation from early childhood, suggesting that effective oral health education may play a supportive role in optimizing both preventive and orthodontic outcomes (9,10).

The objectives of school-based prevention extend beyond teaching correct oral hygiene techniques and include dietary education, with particular emphasis on increasing awareness of cariogenic foods to limit and healthier alternatives to encourage for the protection of dental health. Traditional school-based oral hygiene programs generally rely on frontal lectures, static visual aids, and demonstrations using dental models. Although these approaches convey theoretical knowledge, they often fail to sustain children's engagement and motivation and may not be fully suited to the cognitive and developmental characteristics of younger learners, who primarily acquire knowledge through direct experience and sensory exploration (11,12).

In this context, Montessori pedagogy, developed by Dr. Maria Montessori, offers a child-centered educational approach based on the principles of autonomy, experiential learning, and multisensory engagement. This method recognizes the child as an active participant in the learning process and is grounded in scientific observation of different developmental stages, during which children show heightened readiness to acquire specific skills (13). A core concept of the Montessori method is respect for individual timing and learning rhythms, in contrast to traditional educational models that emphasize passive and standardized transmission of information.

Montessori classrooms promote learning through active manipulation of educational materials, freedom of exploration, and spontaneous repetition of experiences, enabling children to internalize knowledge in a natural and lasting manner (14). This innovative approach differs substantially from traditional teaching methods, in which the educator assumes a central role and the child remains a largely passive recipient of information.

The application of Montessori principles to oral hygiene education appears particularly promising, as it allows children to learn fundamental preventive concepts through play, simulation, and the construction of concrete representations of dental structures and oral hygiene tools. In this framework, play assumes a central educational role, positioning the child as the protagonist of the learning process and fostering the development of motor, cognitive, and emotional skills related to self-care (15).

Numerous recent studies have demonstrated the effectiveness of Montessori-based oral health education interventions, highlighting significant improvements in both theoretical knowledge and oral hygiene behaviors, particularly in terms of the frequency and quality of toothbrushing among school-aged children (16,17). These findings support the hypothesis that multisensory, child-centered educational approaches can produce more stable and long-lasting behavioral changes compared with traditional educational models (15).

In pedagogy, the analysis of children's drawings also plays a significant role, as it provides a privileged expressive tool to understand their inner world, including perceptions, emotions, knowledge, and mental representations. Drawing represents a form of spontaneous communication that allows children to express ideas and experiences they may not be able to verbalize, especially in early developmental stages when language skills are still limited (18,19). Through graphic production, cognitive, affective, and social dimensions can be explored, as cultural, experiential, and relational meanings emerge from the signs, symbols, and narrative choices. In educational research, the use of drawings allows access to children's mental models, making visible representations of knowledge, concepts, and relationships that can enrich educational observation and guide more targeted and personalized teaching interventions (20,21).

In light of these considerations, the present study aims to evaluate the impact of a Montessori-based oral hygiene education program in comparison with a traditional educational approach. The analysis integrates cognitive, behavioral, and emotional dimensions of learning, including drawing analysis, in order to provide a comprehensive assessment of the effectiveness of the Montessori method in promoting oral health during childhood.

MATERIALS AND METHODS

The study was conducted within the framework of an educational collaboration between Monte Ortigara Primary School in Cinisello Balsamo (Milan, Italy) and dental health educators. A total of 36 children aged 7 to 9 years were recruited and divided into two equal groups (group A and group B), each consisting of 11 boys and 7 girls.

Group A: Traditional Method

This group participated in a conventional educational program, including:

- Verbal explanation of plaque, caries, and brushing techniques;
- Illustrative posters of healthy and unhealthy teeth;
- Practical demonstration using a dental model, toothbrush, and dental floss;
- Multimedia materials to reinforce daily brushing routines.

Group B: Montessori Method

The Montessori group participated in a child-centered multisensory educational experience, including:

- Modelling teeth and oral cavities using Play-Doh, soft, colorful modeling dough capable of reproducing the shape of teeth and dental arches;
- Crafting cardboard tooth shapes to explore structure and function;
- Food collages to classify cariogenic and non-cariogenic foods;
- Sensory exploration of toothpaste focusing on taste, smell, and texture;
- Memory games to reinforce brushing sequences;
- Creation of a personalized "toothbrush book" with illustrated rules for correct oral hygiene.

Project Structure

The project was organized into four distinct phases.

Phase I consisted of an introductory meeting with presentation of the project, collection of medical history and informed consent, and an initial dental assessment. Children were also asked to create a drawing on the theme: "Your experience at the dentist".

Phase II consisted of an operational meeting including transmission of information on correct oral hygiene practices, dietary education, and pathophysiological principles of caries-related diseases, according to the methods specific to Groups A and B.

Phase III consisted of re-evaluation (after 3 months) with observation of changes following the operational meeting. Group A completed a multiple-choice test to evaluate knowledge acquisition and Group B was asked to independently create a Play-Doh oral model. Both groups were asked to produce a new drawing representing their dental experience to assess the relational experience between child and dental operator.

Phase IV consisted of experience verification. After a briefing on the concepts learned, children were asked to create an additional drawing to represent the relationship between the dentist and the child patient. Two main assessment tools were used for evaluation:

1) Medical history questionnaire (Phase I and phase III):
    - Frequency of dental visits;
    - Emotional perception of dental visits;
    - Daily brushing frequency;
    - Self-reported brushing technique.
2) Drawing analysis:
    - Use of color and level of detail;
    - Representation of the dentist and dental environment;
    - Indicators of fear (shadows, dark colors, erasures, rigid postures);
    - Presence of positive symbols (smiling figures, bright colors, symmetry).

RESULTS

Knowledge Improvement

Both groups showed an increase in basic oral health knowledge. Group A demonstrated modest gains, whereas Group B exhibited more marked and consistent improvements. Children in the Montessori group were more likely to describe plaque formation, distinguish between healthy and harmful foods, and explain the importance of brushing.

Dental Visit Frequency and Attitudes

Group B reported a slight increase in the number of children who had recent dental visits (the number increased from 14 to 16 between phase I to phase III) (Fig.1a) and a higher proportion of positive attitudes toward dental care (Fig.1b).

While changes were modest, emotional shifts were evident in both questionnaires and drawings.

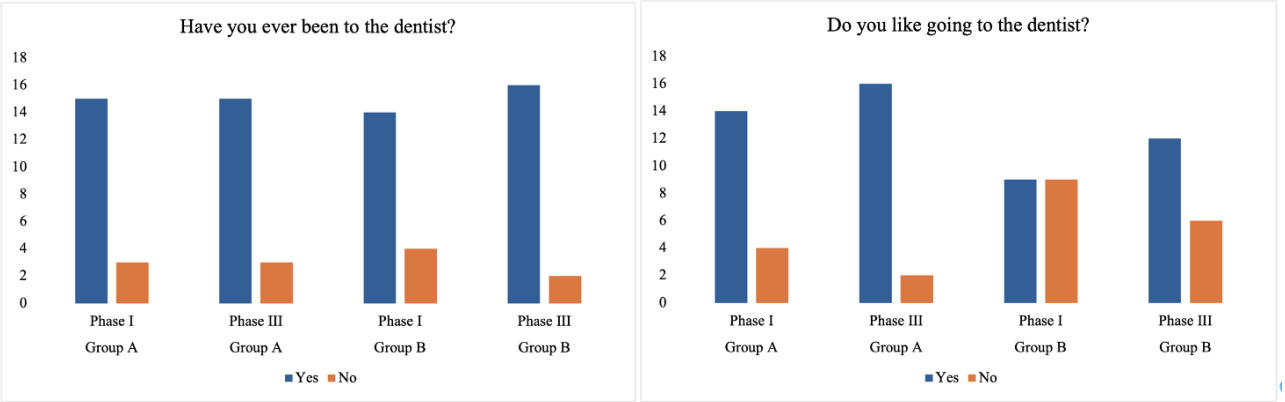

Fig. 1. ***(a)*** *Number of subjects who underwent dental examinations in phases I and III in groups A and B.* ***(b)*** *Number of subjects who like going to the dentist in phases I and III in groups A and B.*

Behavioral Changes in Brushing

Brushing frequency increased in both groups; however, the Montessori group more frequently adopted twice-daily brushing (Fig.2). Children in this group also exhibited greater enthusiasm for brushing, consistent with literature on multisensory engagement. Additionally, there was an increase in the use of the modified Bass technique (circles movements), particularly in Group B (Fig.3), considered the most effective method for maintaining proper oral hygiene (22,23).

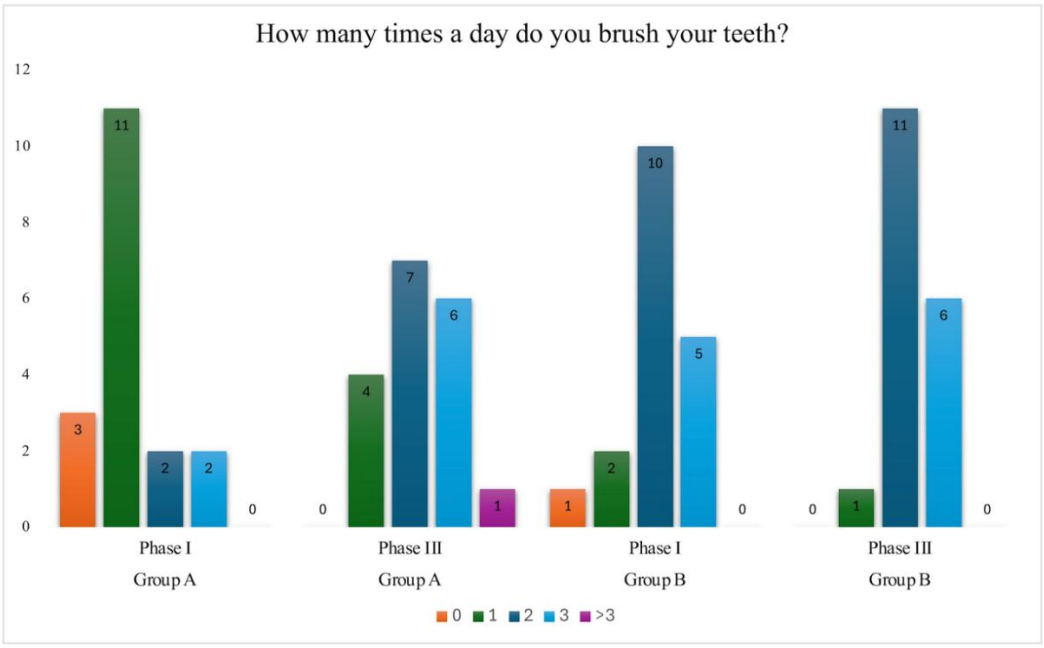

Fig. 2. *Distribution of subjects based on daily brushing frequency in phases I and III in groups A and B.*

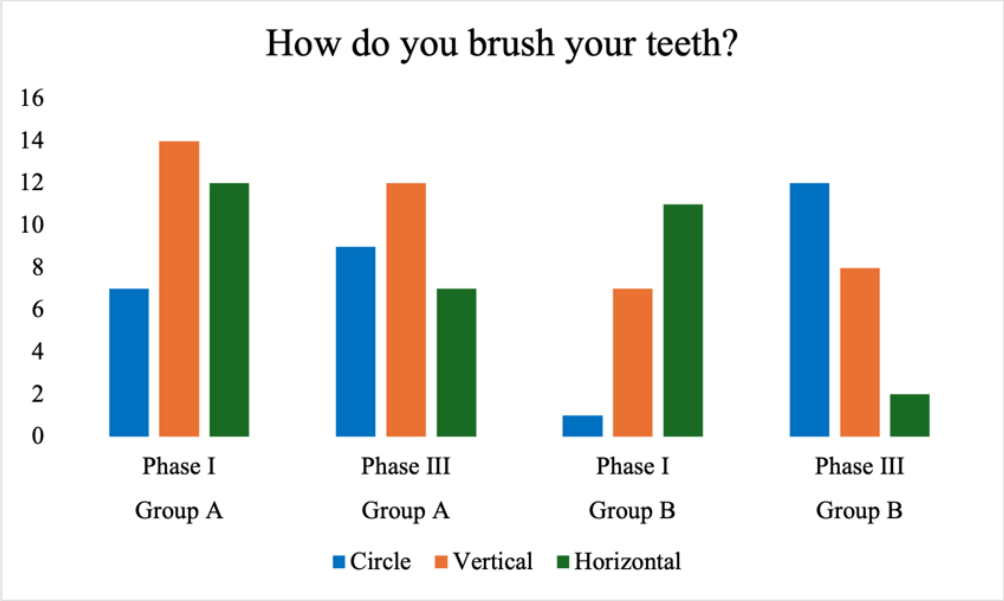

Fig. 3. *Distribution of subjects based on brushing technique in phases I and III in groups A and B.*

Drawing Analysis

Distinct differences were observed between the two groups.

Group A: Traditional Method

Drawings produced by children in Group A, treated with the traditional method, are characterized by sparse settings, often limited to the dental chair and in some cases visually merged with the subject. The environments frequently include oppressive elements, such as low ceilings or confined spaces, and show limited attention to detail. Emotional discomfort and anxiety are suggested by the frequent presence of erasures. Figures tend to appear rigid and static, and in many cases either the dentist or the patient is absent, resulting in a lack of interaction. The use of color is predominantly dark or minimal, and the dental mirror is rarely represented as a "communication bridge." Overall, these drawings convey a passive and unenthusiastic attitude toward the dental experience (Fig.4).

Fig. 4. *Drawing by a girl in group A at stage IV. There is lack of details, the use of colors is limited, and the patient depicts herself with tears in her eyes, indicating distress.*

Group B: Montessori Method

In contrast, drawings from Group B, treated with the Montessori method, display rich and detailed settings with careful attention to detail. Facial expressions are predominantly calm and smiling, and colors are used in a full and

vivid manner. The scenes frequently depict physical proximity and direct contact between the operator and the patient, emphasizing a relational dimension of the dental encounter. The dental mirror is often represented as a "communication bridge," reinforcing its communicative role. Collectively, these features reflect a constructive, participatory, and enthusiastic attitude toward the dental experience (Fig.5).

Fig. 5. *Drawing by a girl in group B at stage IV. The setting is characterized by many details, and the use of color is very prominent. Note the reassuring gaze of the parent accompanying the child to the doctor, who is portrayed as the figure capable of resolving the problem causing the pain.*

DISCUSSION

The clear advantage observed in the Montessori group supports the hypothesis that experiential, active, child-guided learning fosters a deeper understanding of proper oral hygiene practices and enhances motivation to maintain them.

These results are consistent with orthodontic evidence indicating that early preventive and therapeutic interventions can positively affect functional and skeletal outcomes, provided that adequate patient cooperation is achieved. In this perspective, educational approaches aimed at increasing children's awareness, autonomy, and engagement may represent a crucial adjunct to clinical orthodontic protocols, supporting long-term stability and functional benefits (24,25).

Montessori-based activities provide tactile and sensory stimulation, reinforce individual autonomy, and support cognitive development through meaningful and contextualized tasks, enabling children to internalize knowledge and skills naturally and sustainably (14).

These findings are consistent with international studies demonstrating that playful, multisensory Montessori interventions produce statistically significant improvements in both knowledge and brushing behaviors in children (15,17). The consistency of results across culturally and methodologically diverse contexts highlights the robustness and transferability of Montessori principles.

Theoretically, Montessori pedagogy engages multiple sensory channels and positions the child as the active constructor of knowledge. This aligns with contemporary cognitive theories emphasizing the importance of manual interaction and direct experience in memory consolidation and skill acquisition (26). Furthermore, the nonjudgmental and secure Montessori environment may reduce dental anxiety, a known factor associated with avoidance of dental visits and poor adherence to preventive practices (21).

Strengths of the Study

This study is strengthened by the integration of an in-depth emotional analysis based on children's drawings, enabling the exploration of relational and affective dimensions often overlooked in traditional assessments. The implementation in

a real school setting provides practical educational implications. Furthermore, the direct comparison between traditional and Montessori methodologies, combined with a multidimensional assessment of cognitive, behavioral, and emotional domains, offers a comprehensive evaluation of the intervention.

Limitations

The main limitations include the small sample size, which may reduce statistical power, and the absence of direct clinical measures such as plaque and bleeding indices. In addition, the lack of long-term follow-up prevents evaluation of the persistence of behavioral changes.

Future Perspectives

Future studies should include larger randomized controlled trials, incorporate objective clinical indicators, and assess the long-term stability of the observed behaviors.

CONCLUSIONS

The results clearly indicate that Montessori-based oral hygiene education provides significant advantages over traditional methods, improving knowledge, behaviors, and children's emotional comfort. Considered alongside international evidence, a consistent picture emerges: multisensory, child-centered learning significantly enhances the effectiveness of oral health education interventions. These findings suggest that incorporating Montessori principles into school-based dental prevention programs could promote lasting protective behaviors, support children's emotional well-being, and provide a replicable model across diverse educational contexts.

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Conflict of interest

The authors declare that they have no conflict of interest.

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Review

CORRELATIONS BETWEEN PERIODONTAL DISEASE, TYPE 2 DIABETES, AND HEMATOLOGICAL BIOMARKERS: A NARRATIVE REVIEW

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INTRODUCTION

Periodontal disease and type 2 diabetes mellitus (T2DM) share a well-documented bidirectional relationship. Both conditions are characterized by chronic inflammation, which is reflected in measurable systemic alterations such as erythrocyte sedimentation rate (ESR), white blood cell count (WBC), red cell distribution width (RDW), and mean platelet volume (MPV). This narrative review summarizes the available evidence on the link between these hematological parameters, periodontitis, and type 2 diabetes, discussing the underlying pathophysiological mechanisms and clinical implications.

Periodontitis is a chronic inflammatory disease of bacterial origin that affects the tissues supporting the teeth. Type 2 diabetes mellitus is a metabolic disease characterized by insulin resistance and chronic hyperglycemia. Numerous studies have highlighted a bidirectional interaction between the two conditions: diabetes increases susceptibility to and severity of periodontitis, while periodontitis worsens glycemic control.

In addition to the classic inflammatory markers, some studies have highlighted specific alterations in hematological parameters commonly used in clinical practice. Analyzing these correlations can offer useful insights for integrated patient management.

MATERIALS AND METHODS

This narrative review adopted the methodological principles of the PRISMA guidelines to ensure transparency and rigor, although it is not a comprehensive systematic review. A search was conducted on PubMed, Scopus, and Embase, including studies published between 2000 and 2025. The keywords used were: “periodontitis,” “type 2 diabetes mellitus,” “hematological markers,” “sedimentation rate,” “white blood cells,” “RDW,” “MPV,” and “systemic inflammation.” Clinical, observational, meta-analysis, and intervention trials concerning periodontal treatment in diabetic patients were included. Data extraction focused on outcomes related to hematological biomarkers and systemic inflammatory indices. Studies with non-human samples or incomplete data were excluded. This narrative review summarizes clinical, observational, and experimental studies on the hematological biomarkers ESR, WBC, RDW, and MPV in relation to periodontitis and type 2 diabetes. Articles published in the last two decades were considered, including research conducted in the fields of dentistry, endocrinology, and internal medicine (Fig.1).

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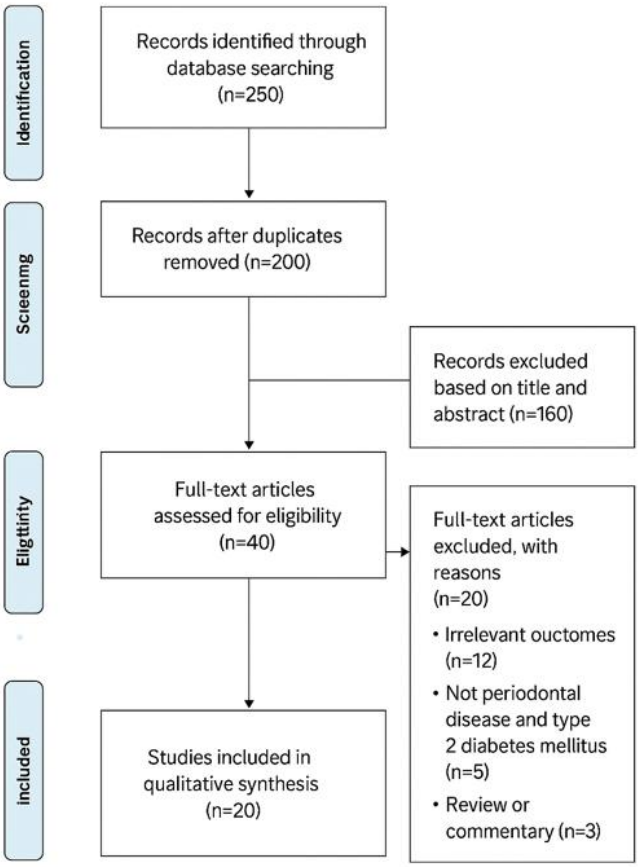

Fig. 1. *This PRISMA flow diagram illustrates the selection process for the studies included in the narrative review. It shows the number of records identified through electronic databases, the number of records screened, the number of studies assessed for eligibility and the number of studies included in the final qualitative analysis after the inclusion and exclusion criteria were applied.*

RESULTS AND DISCUSSION

The relationship between periodontal disease and type 2 diabetes fits into the concept of "inflammaging" and low-grade chronic inflammation, which are increasingly recognized as central elements in the pathophysiology of metabolic and immune conditions. The interaction between glycemic alterations, oral dysbiosis, and compromised immune response creates a vicious cycle that amplifies the systemic effects of the two conditions.

Expansion of pathophysiological mechanisms

Periodontitis causes an immune response characterized by an increase in pro-inflammatory cytokines, such as interleukin 1 beta (IL-1β), interleukin 6 (IL-6), tumor necrosis factor alpha (TNF-α), and C-reactive protein (CRP). This systemic increase in inflammatory mediators interferes with insulin signaling, accentuating insulin resistance, one of the hallmarks of type 2 diabetes. At the same time, hyperglycemia promotes the formation of advanced glycation end products (AGEs), which amplify the inflammatory response and worsen the destruction of periodontal tissue.

Impact on hematological biomarkers

Analysis of hematological parameters provides a quantitative view of the systemic effects of these two diseases.

In ESR, its increase is an indirect but sensitive indicator of chronic inflammation, even in other systemic diseases. Persistently high values in patients with periodontitis and type 2 diabetes suggest the presence of a systemic inflammatory cascade that is not fully compensated. ESR increases in conditions of systemic inflammation. In periodontitis, the accumulation of pathogenic bacteria and the local immune response cause the release of pro-inflammatory cytokines, such as IL-6 and TNF-α, which increase hepatic production of acute phase proteins. In type 2 diabetes, chronic

hyperglycemia causes oxidative stress and low-grade inflammation. The coexistence of the two conditions amplifies these processes, resulting in significantly higher ESR values.

In WBC, A mild increase, often characterized by neutrophilia, indicates a state of constant immune activation. In diabetic patients, reduced neutrophil function causes the immune system to compensate with an increase in quantity. Periodontitis involves sustained neutrophil activation, with an increase in WBC count. Similarly, type 2 diabetes is associated with a slight increase in white blood cells, due to chronic inflammation and immune dysfunction induced by hyperglycemia. The interaction between the two pathological states can lead to more pronounced leukocytosis, reflecting combined immune activation.

In RDW, increased erythrocyte variability reflects not only alterations in bone marrow function, but also oxidative stress and metabolic disorders typical of diabetes. Elevated RDW values are also correlated with cardiovascular risk, further linking periodontitis and diabetes to conditions such as atherosclerosis and metabolic syndrome. RDW is an indicator of red blood cell size variability. Both conditions are associated with an increase in RDW: in periodontitis, due to the inflammatory response that affects iron metabolism; in T2DM, due to the presence of oxidative stress that alters red blood cell deformability. Elevated RDW is also associated with increased cardiovascular risk, a risk common to both periodontitis and T2DM.

MPV represents an important marker of thrombotic risk. Increased MPV in patients with both conditions suggests a state of platelet hyperreactivity with potential implications for cardiovascular risk. MPV is a marker of platelet activation. In periodontitis, chronic inflammation stimulates the bone marrow to produce larger and more reactive platelets. Type 2 diabetes is characterized by platelet hyperactivity, which contributes to thrombotic predisposition. The coexistence of the two diseases further enhances the increase in MPV, indicating an accentuated pro-thrombotic profile.

Interdisciplinary implications

The intersection between periodontitis and type 2 diabetes highlights the need for integrated clinical management. Clinical studies have shown that non-surgical periodontal treatment can improve glycemic control, with reductions in glycated hemoglobin (HbA1c) ranging from 0.3% to 0.6%. This not only highlights the role of periodontitis as a modifiable risk factor in diabetes but also lays the foundation for close collaboration between dentists, diabetologists, and general practitioners. The joint alteration of the biomarkers ESR, WBC, RDW, and MPV in patients with periodontitis and type 2 diabetes (T2DM) suggests that these parameters can be used as integrative indicators for the diagnosis and monitoring of the disease. Periodontal treatment appears to improve glycemic control and reduce certain inflammatory markers, suggesting a potential systemic therapeutic role.

CONCLUSIONS

The literature confirms that periodontitis and type 2 diabetes share a common inflammatory substrate that is reflected in specific hematological alterations. Increased ESR, WBC, RDW, and MPV indicate systemic inflammation amplified by the concomitant presence of the two conditions. A multidisciplinary approach can improve clinical outcomes and overall patient management.

Although the literature is rich in studies confirming the correlation between these two conditions, there are still some methodological gaps. Most studies are observational in nature, making it difficult to establish direct causality. Further randomized trials and longitudinal studies could better clarify the long-term impact of periodontal therapy on hematological parameters and metabolic outcomes. In addition, it would be useful to investigate the role of the oral and systemic microbiome, a rapidly expanding area of research.

Conflict of interest

The author declares that they have no conflict of interest.

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BIOLOGICAL MECHANISMS AND DETERMINANT FACTORS OF OSSEOINTEGRATION: FROM CELL BIOLOGY TO CLINICAL PRACTICE

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ABSTRACT

Introduction: The surgical placement of dental implants initiates a complex biological healing process, essential for the success of osseointegration. This process involves various biological mechanisms that determine the outcome of the integration between the implant and the surrounding bone. *Materials and Methods:* This review critically analyses the literature on the biological mechanisms involved in osseointegration. Key factors such as the phases of primary healing, bone maturation, and the importance of implant surface properties, including geometry, chemical composition, and topography, on cell interaction and bone regeneration are highlighted. *Discussion:* The initial phase of healing involves the formation of a stable fibrin matrix that facilitates the migration of mesenchymal stem cells and their differentiation into osteoblasts, while angiogenesis ensures an adequate supply of nutrients. The subsequent remodelling phase is crucial for transforming immature bone into structurally superior lamellar bone, which is vital for the long-term stability of the implant. Additionally, the importance of careful implant site preparation is discussed, highlighting periosteal integrity, temperature control, and insertion torque, which directly influence osteogenetic outcomes. *Conclusion:* Through a synthesis of current literature on these critical factors, this work offers insights for optimising clinical practices to improve implant success rates. Ultimately, the results contribute to advancements in implantology and strategies for effective bone regeneration.

KEYWORDS: *Osseointegration, implant healing phases, titanium implant surfaces, surface modification of dental implants, implant site preparation, insertion torque*

INTRODUCTION

The surgical placement of an implant marks the crucial moment when not only the procedure begins, but also the intricate biological process of healing. The surgical procedure itself causes controlled damage to the surrounding soft and hard tissues, immediately triggering an inflammatory response. This reaction is the body's fundamental mechanism, aimed at repairing and, ideally, regenerating damaged tissue (1). A deep understanding of the biological mechanisms underlying this process is crucial for improving the clinical success of implants and for transcending current limitations in osteointegration. In this context, age-related changes and their influence on bone tissue quality, which is crucial for the healing process, are also relevant (2). The process of osseointegration can be divided into two main phases: primary healing and bone maturation. During the initial phase, which is based on the formation of primary bone, rapid restoration

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of bone integrity occurs through biological mechanisms involving blood coagulation, the formation of a fibrin clot, and the migration of mesenchymal stem cells that differentiate into osteoblasts. This phase is essential not only for the formation of an initial bone matrix, but also for the subsequent development of angiogenesis, which is crucial for ensuring an adequate supply of oxygen and nutrients. The correct progression of these events is crucial for the success of the plant. In the subsequent phase of bone remodelling and maturation, the dynamics of osteoclastic resorption and osteoblastic deposition become relevant, as they ensure the transformation of immature bone into lamellar bone, which is structurally and functionally superior. This continuous remodelling process is crucial for the long-term stability of the bone-implant interface and for preventing complications such as marginal bone resorption and fibrointegration. Another crucial element for successful osseointegration is the surface properties of the implants. The geometry, chemical composition, and topography of implant surfaces directly influence the initial interactions between bone cells and the implant itself. In recent decades, research has shown how rough and specifically designed surfaces can significantly improve cell adhesion and promote a favourable environment for bone regeneration. Finally, the preparation of the implant site is a determining factor for the success of osseointegration. Careful management of the periosteum, the required osteotomy, and temperature control during insertion are all aspects that can compromise bone regeneration and, consequently, the final outcome of the implant. In this article, we will explore in detail the various biological factors that influence osseointegration, analysing the underlying mechanisms of each stage of the healing process and the importance of implant surfaces and site preparation. We will delve into how each aspect can be optimised to ensure more effective bone integration, thus contributing to the clinical success of implants.

MATERIALS AND METHODS

This review is based on a critical analysis of international scientific literature to explore in detail the biological mechanisms, surface factors, and clinical considerations that influence the process of osseointegration.

Sources and Search Criteria

Databases: The research was conducted primarily on electronic biomedical databases, including PubMed (MEDLINE) and Scopus, using a combination of keywords and MeSH terms.

Keywords: The main search terms included: "Osseointegration", "Implant Healing Phases", "Titanium Implant Surfaces", "Surface Modification of Dental Implants", "Microroughness and Nanoroughness", "Implant Mechanical Properties", "Implant Site Preparation", and "Insertion Torque".

Reference Period: Priority has been given to the most recent articles, but key historical studies and systematic reviews (such as the work of Brånemark and Albrektsson), considered milestones in understanding the biological process, have also been included.

Types of Studies Included: In vivo articles (animal models and human clinical studies), in vitro studies (analysing cell-material interactions), systematic reviews, meta-analyses, and review articles that addressed the properties of biomaterials and the biological stages of osseointegration were selected.

Data Extraction

For each selected article, information related to the following key areas was extracted, as described in the article: Details on the mechanisms of coagulation, angiogenesis, cell differentiation (MSCs into osteoblasts), and bone remodelling (osteoclasts/osteoblasts); impact of topography (macro, micro, nano), chemistry (e.g., Anodic Oxidation, SLA, DCD), and coatings (e.g., Hydroxyapatite) on cellular response; analysis of the influence of the elastic modulus (stress shielding), porosity, hydrophilicity, and crystallinity; Finally, the importance of periosteal integrity, thermal management during osteotomy, and the impact of insertion torque on primary stability and healing.

Synthesis and Interpretation

The extracted data was synthesised and thematically organised to provide a comprehensive overview of osseointegration as a dynamic process. The interpretation of the results was guided by the principle of clinical translation, highlighting the direct correlations between basic discoveries and optimised clinical practices, as described in the following sections.

DISCUSSION

Biological Factors in Osseointegration

Osseointegration is a complex and multiphasic biological process, governed by a synergistic cascade of cellular and molecular events that determine its clinical success. Healing occurs through the critical interaction of local and systemic factors and is classically divided into two main phases: the formation of primary bone and its subsequent remodelling and maturation.

- Phase 1 - Primary Healing and Bone Formation (Intramembranous): The initial phase is characterised by rapid intramembranous bone healing. Critical processes include blood coagulation immediately after implant insertion and the formation of a stable fibrin matrix. This clot serves as an essential three-dimensional scaffold for the migration and differentiation of primitive and mesenchymal cells from adjacent tissues. The extent and stability of the clot are crucial, as they define the potential area for bone regeneration. A fundamental aspect of this phase is angiogenesis, the development of new blood vessels, which is vital for establishing the necessary vascular supply, providing oxygen, nutrients, and progenitor cells to the implantation site. In parallel, osteoblasts differentiate from mesenchymal stem cells (MSCs). MSCs migrate to the area and differentiate into osteoblasts, a process powerfully stimulated by growth factors and signalling molecules, such as Bone Morphogenetic Proteins (BMPs) and Transforming Growth Factor-beta (TGF-beta) (3). Understanding the sources and mechanisms of MSC osteogenic differentiation is crucial for optimising bone regeneration (4). As early as the first day, pre-osteoblasts and osteoblasts adhere to the implant surface, particularly to the afibrillar calcified layer, to deposit collagen fibrils that make up the extracellular matrix. The subsequent mineralisation of this matrix leads to the early deposition of immature (or woven) bone directly in contact with the implant surface, achieving early biological fixation of the device (5). The primary goal at this stage is to quickly fill the space created by the new installation.
- Phase 2 - Bone Remodelling and Maturation: The second phase is dominated by the remodelling of the newly formed bone tissue. This phase involves the balanced and coordinated activity of both osteoclasts, specialised cells responsible for primary bone resorption, removing old, damaged, or woven bone tissue, and osteoblasts, which act to deposit new tissue, replacing woven bone with lamellar bone, which is highly organised and mechanically more resistant (6). This continuous cycle of resorption and deposition ensures the maintenance of bone quality and density, facilitating the structural and functional adaptation of the bone-implant interface, culminating in the process of mature osseointegration. However, it is crucial to address complications such as peri-implantitis, which can compromise the success of dental implants. Recent studies have demonstrated the effectiveness of innovative approaches in managing such complications as electrolytic cleaning and regenerative therapy, which can improve clinical outcomes in cases of peri-implantitis (7), he treatment of oral mucositis using platelet-rich fibrin (8,9) or periodontal treatment and the use of complementary therapies play a role in optimising the peri-implant environment (10). In this context, it is important to highlight the local inflammatory responses that can influence bone tissue healing (11). Proper management of local inflammation is essential for promoting effective bone integration, and this can also be influenced by the drugs taken (12).

Importance of Implant Surfaces

The surface properties of the implant are a determining factor in modulating osseointegration, directly influencing the initial interactions between proteins and cells (13,14). It is widely recognised that the geometric design, chemical composition, and, in particular, the surface topography of the implant have a significant impact on the success of peri-implant tissue healing.

1. Topographic Properties: There has been a crucial transition from smooth surfaces (obtained by turning), whose healing time could extend up to 3-6 months (15), to the current moderately rough surfaces. These topographical imperfections are essential as they provide optimal sites for bone adhesion and deposition by osteogenic cells, establishing the bone-implant interface. The induced surface roughness can be accurately categorised into three dimensional scales, each with distinct implications for biological performance: Macro, micro, and nano-roughness (16) (Table I).

Table I. *Topographic properties.*

Roughness Scale	Typical Dimensions	Features	Primary Biological Role
Macroroughness:	Millimetres - Micrometres	Overall structure, threads, porosity	Primary Stability (mechanical fixation)
Microroughness:	Micrometric Level	Obtained through sandblasting, acid etching, anodising	Osteoblast adhesion and cell growth (better osseointegration)
Nanoroughness:	Below 100 nm	Fine irregularities (<100 nm)	Osteoblast proliferation, increased protein adsorption (fibronectin, vitronectin), anti-biofilm action

Both microroughness and nanoroughness on titanium surfaces are crucial for bone-titanium integration (17,18). Rough surfaces facilitate the adhesion and differentiation of osteoblast-like cells (19,20). At the molecular level, these roughness levels optimise critical parameters such as alkaline phosphatase (ALP) activity and osteoconductivity (21). Specifically, the nanoroughness creates a highly favourable microenvironment for osteoblast proliferation and, an innovative aspect, demonstrates an intrinsic ability to counteract bacterial adhesion and biofilm formation, significantly reducing the potential risk of peri-implantitis (18). Rough surfaces can be further distinguished into two categories: Without Coating, obtained through mechanical and chemical procedures (e.g., Sandblasting and Acid Etching, SLA) and with Coating, meaning surfaces treated with the addition of a material, such as titanium plasma spray (TPS) or Hydroxyapatite (HA) (22). Although topography is considered more influential than surface chemistry in promoting early healing (23), applying a calcium phosphate coating, particularly HA, can offer distinct benefits. HA accelerates peri-implant osteogenesis (24) and can act as a mechanical barrier, reducing the release of metal ions or the detachment of titanium particles (25,26). Calcium phosphate coatings increase protein adsorption, promoting platelet adhesion and activation, and fibrin binding, thus accelerating healing (23). The use of hydroxyapatite-based biomaterials is not limited to direct implant coatings but is also crucial in auxiliary techniques such as Guided Bone Regeneration (GBR), where materials like titanium-reinforced membranes and synthetic nanocrystalline hydroxyapatite demonstrate excellent clinical and histological results in promoting new bone formation (27). Comparative studies have shown that HA-coated implants exhibit earlier bone formation compared to sandblasted titanium implants (28). It is important to note that the bone-implant interface, characterised by a thin, calcified, afibrillar layer, is structurally similar for both rough metal surfaces and those coated with HA. This suggests that the primary bond in both cases is achieved through the micro-mechanical interdigitation of the cement line with the surface irregularities of the material (23). Furthermore, it is crucial to consider the importance of decontaminating implant surfaces. Innovative techniques can improve the cleaning of the implant-abutment surfaces, contributing to better osseointegration and reducing the risk of complications (29).

2. Chemical Properties: Changes in surface roughness are intrinsically linked to alterations in the implant's surface chemistry (30). The techniques used to produce advanced surfaces involve intense chemical reactions that leave specific imprints on the titanium (Ti) substrate, including the presence of residual ions from the acid (etching), sandblasting residue, or chemical influence from the electrolyte (oxidation). By carefully selecting the production process, it is possible to synergistically optimise the chemical characteristics of the plant. Some of the main techniques:
   - Anodic Oxidation (AO): an electrochemical technique used to create a thicker and more structured surface oxide layer. In the process, the implant is placed at the anode of an electrolytic cell. Applying a specific voltage induces redox reactions that generate a continuous cycle of oxide film formation and removal. This process culminates in the creation of a porous structure at the micro/nanoscopic scale (31). Anodisation allows for the regulation of surface charge, a relevant aspect since electrical stimulation can promote osteogenesis through interactions with naturally charged biomolecules (32). Furthermore, experimental results indicate that nanostructured surfaces obtained through AO, particularly at the implant neck level, promote the adhesion, proliferation, and extracellular matrix deposition by human gingival fibroblasts (33), which is essential for establishing a tight seal of the peri-implant soft tissues.

- Double Acid-Etched with Calcium Phosphate Coating (DCD): The DCD technique (Double Acid-Etched with Calcium Phosphate Coating) combines a double etching treatment with the deposition of nanoparticles. Calcium phosphate (CaP) nanoparticles are deposited onto the surface previously treated with double etching, typically using sol-gel technology. These nanoparticles, which can make up as much as 50% of the surface (34), exert a strong chemical attraction to the implant surface (35,36). The presence of calcium phosphate mimics the mineral composition of bone, and this technique has been shown to be effective in reducing bacterial adhesion to the implant surface (37).
- Sandblasting and Double Acid Etching (SLA): The SLA technique represents a clinical standard and is based on two sequential subtractive steps to generate an optimised surface morphology. A first phase of sandblasting with titanium oxide creates the surface microroughness. This is followed by acid etching (often hydrofluoric acid), which refines and shapes the nanostructure. One of the most studied effects of this technique is the accumulation of fluorine (F) on the surface, which leads to modified SLA surfaces (SLActive, Ti-U). It is hypothesised that fluorine-containing surfaces enhance the host-implant reaction in early osseointegration (38). These surfaces promote a branched cellular morphology and an osteogenic gene expression profile in osteoblasts and improve osteoinduction and osteogenesis in stem cells.
- Laser Ablation: Laser ablation is a precision technique that offers micrometric and nanometric control over topography. The technique uses laser pulses to create highly precise micro and nanochannels on the implant surface. The laser-generated topography is specifically designed to create a biological seal at the implant neck level. This is achieved by selectively stimulating the adhesion and growth of connective and bone tissue, while discouraging the apical migration and growth of the junctional epithelium (39), a key factor for the long-term stability of peri-implant soft tissues. Recent studies have also highlighted how laser-induced microtopographies can positively influence the proliferation of human osteoblasts and bone deposition, contributing to osseointegration (40).
- Treatments with Bioactive Nanoparticles: In addition to calcium phosphate nanoparticles, research is focussing on integrating other bioactive nanoparticles onto titanium surfaces. For example, the application of Vitamin D nanoparticles has shown promising results in modulating bone healing patterns, an aspect particularly relevant in complex clinical settings such as osteoporotic patients, where bone regeneration is challenged (41,42).

3. Mechanical Properties: To ensure rapid, stable, and long-lasting bone integration, research on implant biomaterials has focused on optimising their mechanical properties. Once osseointegration is achieved, the proper transfer of masticatory stress to the surrounding bone tissue is of fundamental importance. A significant discrepancy in the elastic modulus (stiffness) between the implant material and the peri-implant bone can trigger the stress shielding phenomenon. This imbalance in load transfer is a known cause of marginal bone loss, inevitably compromising the long-term success of the implant (43). Finite element analysis (FEA) has determined that an excessively high elastic modulus of the implant material negatively impacts the stress and strain distribution in the peri-implant bone (44). To mitigate the risk of stress shielding, the primary goal in biomaterial development is to reduce the stiffness of the implant material, bringing it as close as possible to that of natural bone (approximately 10-30 GPa). Historically, the market was dominated by commercially pure titanium (CP). Grade 1. Evolution has led to the prevalent use of CP Grade 4-5 titanium or high-strength alloys like Ti-6Al-4V and TiZr, where a slight increase in Iron (Fe) and Oxygen (O) provides greater hardness. However, the frontier of research lies in the development of low elastic modulus Titanium-based alloys, incorporating elements such as Zirconia (Zr), Niobium (Nb), Tin (Sn), Tantalum (Ta), Silicon (Si), and Iron (Fe), to achieve an ideal mechanical profile. A prominent example is the Ti-24Nb-4Zr-8Sn alloy (Ti2448), which is distinguished by an extremely low elastic modulus while maintaining high strength and low cytotoxicity (45,46). In addition to the alloy composition, the porosity of the implant surface is another crucial mechanical property. The adoption of a porous structure in biomaterials not only promotes better mechanical integration through potential bone growth into the pores (bone ingrowth) (47), but also acts as an intrinsic mechanism to optimise the mechanical response. Indeed, the controlled increase in porosity has a direct and significant impact on the physical properties, always leading to a reduction in the overall elastic modulus of the material (48), further contributing to mitigating stress shielding. This porosity is not just a mechanical feature, but a powerful biological factor. In vivo studies have fabricated Ti scaffolds with an average pore size of 313-390 μm, demonstrating that such structures optimise the proliferation and differentiation of bone marrow mesenchymal stem cells (in vitro), effectively promoting bone defect regeneration (in vivo) (49). Controlled porosity is,

therefore, a critical parameter that combines the optimisation of the mechanical response with the enhancement of osteogenesis.

4. Physical Properties: Osteointegration is significantly influenced by two key physical properties: surface wettability (hydrophilicity) and crystallinity. Hydrophilicity is quantified by the contact angle with water, with values close to 0° for highly hydrophilic surfaces and greater than 90° for hydrophobic ones. Although titanium is inherently hydrophilic, many commercial implant surfaces tend to become hydrophobic due to processing techniques and surface contamination by hydrocarbons (30). Hydrophilicity is modulated by hierarchical surface roughness and high interfacial energy, as non-optimal roughness can trap air, reducing wettability (50). High hydrophilicity is crucial as it ensures the preservation of the conformation and function of adsorbed plasma proteins, such as those containing the RGD peptide, which are essential for cell adhesion and migration (51). This favourable environment accelerates the differentiation and maturation of osteoblasts, thus promoting early osseointegration (52). In vitro and in vivo studies have shown how hydrophilic surfaces promote faster cell activation and differentiation compared to hydrophobic ones (53,54). To impart hydrophilicity, techniques such as UV irradiation, plasma immersion ion implantation (PII), or drying potassium phosphate salt ions (55,56) are used. However, its hydrophilicity and high surface energy make titanium susceptible to biological ageing (implant surface ageing), a degradation process that can affect interactions with bodily fluids (57). Although high hydrophilicity can counteract hydrocarbon accumulation and ageing (58), the durability and unique clinical benefits resulting from this characteristic still require greater scientific clarity. Regarding crystallinity, titanium dioxide can exist in three distinct crystal structures: rutile (the most common form), anatase, and brookite. The implications of these different structures on the biological response are not yet fully understood. Some studies have suggested that crystallinity may influence protein adhesion, playing a role in the healing process (59), while more recent research has not found a significant impact on the long-term viability of pre-osteoblasts and fibroblasts (60).

Implant Site Preparation

The surgical site preparation phase is a crucial moment that decisively influences the variables related to osseointegration and the long-term success of the implant. Technological advancements have introduced innovative approaches, such as virtual patient protocols, which improve the accuracy of pre-surgical planning (61). A fundamental aspect to consider is the integrity of the periosteum during the procedure. When a full-thickness flap is performed to expose the alveolar crest, removal or damage to the periosteum negatively impacts bone homeostasis. The main sources of blood supply to the alveolar bone actually pass through the periosteum, ensuring the essential delivery of oxygen and nutrients (62). An intact periosteum provides structural and biological benefits, promoting bone regeneration, as evidenced by studies that have shown that partial-thickness flap preparations maintain significantly better vestibular bone volume compared to full-thickness flaps (63). Among the most relevant stages in preparing the implant bed are osteotomy (milling) and irrigation. Bone milling must be handled with extreme care to prevent thermal bone necrosis, a condition that would irreparably compromise osseointegration. The site must be continuously irrigated with cold saline solution (10-15°C) to limit the heat generated by friction. It is essential that the bone tissue temperature does not exceed 47°, the threshold above which osteocyte damage occurs. The recommended average milling speed is around 800 RPM, as higher speeds would increase thermal friction. It is also clinically crucial to maintain a minimum of 1.5 mm of adjacent surrounding bone, particularly on the vestibular bone wall, to ensure stability and prevent soft tissue recession. Despite the standard protocol, some in vitro and prospective studies propose alternative low-speed and non-irrigation techniques for harvesting viable autologous bone, but their clinical reliability is still considered limited (64). Recent studies demonstrate the effectiveness of innovative techniques in preserving the socket through immediate implant placement, highlighting that a good bone-implant interface can be achieved even after an extraction (65,66). Other innovative techniques like the hybrid funnel technique offer a promising approach to site preparation (67). In this context, the use of bone adhesives represents a further innovation to facilitate bone regeneration and site stabilisation during surgical preparation phases (68). In this scenario, evaluating the survival rate of implants in bone sites regenerated with the aid of innovative biomaterials is crucial to confirm the long-term success of such approaches (69). Insertion torque (IT) is another determining factor for site osteogenesis. The compressive forces transmitted during implant insertion and the microfractures in the bone generated by the osteotomy are stimuli that initiate osteoclastogenesis and the accelerated regional phenomenon, which are fundamental for the proliferation of pre-osteoblasts. High torque is generally considered favourable for improving primary stability and implant integration, as it prevents micromovements that could lead to fibrointegration (70). However, excessive torque can induce microfractures, bone necrosis, and high interfacial stresses, compromising the early vascular stages of osseointegration and long-term durability (71). The placement of implants with

forces exceeding 50 Ncm remains controversial. Although some studies indicate that integration can also occur with high torque if supported by a favourable implant macrogeometry (72), a reasoned approach based on bone density is always recommended to balance primary stability and the risk of pressure necrosis (73).

CONCLUSIONS

Osseointegration is the fundamental biological process through which a direct and stable connection is established, which is essential for the success of dental implants. Understanding the stages of the healing process, from the initial coagulation and angiogenesis mechanisms to subsequent mineralisation and bone remodelling, is essential for improving clinical outcomes and optimising surgical techniques. Biological factors, such as the interaction between bone cells and implant surfaces, and the preparation of the surgical site, prove to be crucial in ensuring effective and long-lasting osseointegration. The surfaces of implants, with their topographical and chemical properties, have been shown to significantly influence cell adhesion and biological response, highlighting the importance of innovative design in the field of biomaterials. Similarly, strict management of implant site preparation, temperature control during insertion, and assessment of insertion torque have been identified as key aspects in reducing the risk of complications and promoting long-term implant success. As research progresses, it is essential that new scientific discoveries are promptly integrated into clinical practice in order to refine more effective osteointegration methods. Systematic investment in the study of biological mechanisms and technological innovations related to implantology will not only increase success rates but will also allow us to overcome future challenges in bone regeneration.

Conflict of interest

The authors declare that they have no conflict of interest.

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THE INFLUENCE OF VITAMIN K NANOEMULSIONS ON OSTEOBLAST REGENERATION AND DIFFERENTIATION ON TITANIUM SURFACES

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ABSTRACT

Introduction: Vitamin K is essential for the carboxylation of proteins involved in bone mineralisation, but its oral bioavailability is often limited and variable. Nanoemulsions (including SNELTs) can improve the solubility and absorption of lipophilic compounds. This study evaluates the impact of vitamin K nanoemulsions on the adhesion, differentiation, and mineralisation of human primary osteoblasts on titanium discs. *Materials and Methods:* Critical literature review of osseointegration focusing on biological mechanisms, implant surface properties, and clinical implications. Searches performed on PubMed and Scopus using targeted keywords/MeSH, prioritizing recent and seminal works. Included in vivo, in vitro, and review studies; excluded non–peer-reviewed and irrelevant reports; selection by multiple reviewers. Data extracted on study design, surface and mechanical features, biological outcomes and clinical relevance; findings synthesized to identify evidence, gaps, and research recommendations. *Discussion:* The treated samples, particularly with 100 µg, showed increased RUNX2 expression, greater adhesion, hyperconfluence, and cellular organisation on the titanium surface. EDS analysis revealed an increase in calcium content in the treated samples, indicative of a greater predisposition to mineralisation. *Conclusions:* Vitamin K nanoemulsions enhance osteogenic differentiation and mineralisation of osteoblasts on titanium surfaces, suggesting a potential improvement in osseointegration, especially in low bone density conditions. Further in vitro and in vivo studies are needed to confirm clinical efficacy and optimise formulations and dosages.

KEYWORDS: *Vitamin K, Nanoemulsions (SNELTs), osseointegration, primary osteoblasts, titanium surfaces*

INTRODUCTION

Vitamin K is not a single type of molecule but rather a family of structurally related molecules derived from different sources that are absorbed in different ways. Due to its half-life of approximately 17 hours and its limited storage in the body, a continuous supply of this nutrient is essential for maintaining physiological functions. Its crucial role in bone health is widely recognised: Vitamin K is essential for the synthesis of crucial proteins for bone health, particularly osteocalcin. This protein helps bind calcium to bones and teeth, promoting strong and healthy structures. In this regard, it is crucial to note that while vitamin K is a key element, vitamin D also plays an indispensable role in supporting calcium

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homeostasis and bone mineralisation (1,2). However, the importance of vitamin K extends beyond the bone matrix. Emerging studies suggest that its deficiency can lead to bleeding and gum inflammation, key indicators of periodontal disease, highlighting how healthy gums are vital for overall dental health, protecting the underlying bone and teeth from infections (3). Despite its fundamental importance, the oral absorption of vitamin K fluctuates both between different individuals and within the same subject, with bioavailability that can vary significantly. This variability poses a significant challenge in ensuring adequate systemic levels and therapeutic efficacy. To overcome these limitations, pharmaceutical innovation has explored advanced formulations, such as nanoemulsions, capable of improving the absorption and stability of lipophilic compounds. This article aims to evaluate the influence of vitamin K nanoemulsions on the regeneration and differentiation of osteoblastic cells on a titanium surface, exploring the potential of these nanotechnology formulations in improving osseointegration and supporting skeletal health.

MATERIALS AND METHODS

Sources and Search Criteria

Approach: Critical analysis of international scientific literature aimed at detailing biological mechanisms, surface factors, and relevant clinical considerations for osseointegration.

Databases and Period: Electronic search conducted primarily on PubMed (MEDLINE) and Scopus; priority to the most recent studies, but also including historical works and fundamental reviews.

Research Strategy: Combined use of keywords and MeSH terms including: "osteointegration", "implant healing stages", "titanium implant surfaces", "surface modification", "microroughness", "nanoroughness", "implant mechanical properties", "implant site preparation ". The search strings were adapted for each database.

Inclusion and Exclusion Criteria: Including in vivo studies (animal and clinical models), in vitro studies on cell-material interactions, systematic reviews, meta-analyses, and reviews on biomaterials and the biological phases of osseointegration. Excluded non-peer-reviewed articles, isolated case reports, and publications not relevant to the central theme.

Study Selection: Initial screening of title/abstract followed by full-text assessment; independent selection performed by multiple reviewers with disagreements resolved through comparison or consultation with a third reviewer.

Data extraction: For each study, data were collected on: experimental design, biological model, surface characteristics (macro/micro/nano topography, chemical treatment, coatings), mechanical parameters (elastic modulus, porosity, torque), biological outcomes (coagulation, angiogenesis, cell adhesion and differentiation, bone remodelling), and clinical relevance. The methodological quality and limitations of the studies are noted.

The results were thematically synthesised with a focus on clinical translation. Whenever possible, the evidence was compared and integrated to highlight convergences, gaps, and recommendations for future research.

DISCUSSION

Vitamin K Mechanisms of Action

Vitamin K plays a crucial role in bone health through multiple mechanisms. Once absorbed through the intestinal mucosa, vitamin K is transported into the mesenteric lymphatic system embedded in chylomicrons, the largest diameter (>75 nm) and lowest density fraction of plasma lipoproteins. It then passes into the bloodstream through the thoracic duct, transported in smaller, denser lipoproteins, VLDLs (Very low-density lipoproteins; diameter: 30-80 nm) and LDLs (Low-density lipoproteins; diameter 18-25 nm), and released into the tissues from these. In our bodies, most of the vitamin K1 present is stored in the liver, while in extrahepatic tissues, vitamin K is primarily found as MK4 (4). It is an essential coenzyme for gamma-carboxylase, which carboxylates glutamic acid residues in vitamin K-dependent proteins, transforming them into gamma-carboxyglutamic acid (Gla). Various proteins, such as osteocalcin, periostin, and matrix Gla protein (MGP), are involved in the regulation of bone mineralisation. Osteocalcin, produced by osteoblasts during mineralisation, has the ability to bind to calcium ions and hydroxyapatite crystals, influencing their size and shape. Complete carboxylation of this protein is not the normal state, and vitamin K supplements can increase its concentrations (5,6). Insulin interacts with decarboxylated osteocalcin, influencing insulin production and secretion and suggesting a link between bone health and glucose homeostasis. Additionally, vitamin K is responsible for other mechanisms, such as regulating gene transcription and inhibiting bone resorption (7). Studies show that vitamin K subtypes, MK-4 and MK-7, can influence inflammatory and apoptotic processes that inhibit bone resorption (8). Numerous studies have shown that low serum concentrations of vitamin K1, high levels of undercarboxylated osteocalcin (ucOC), and reduced dietary intake of vitamin K1 and K2 are associated with an increased risk of fractures. The relationship between vitamin K intake and fracture risk is supported by substantial evidence. There were no benefits for higher levels of intake; Rather, a threshold

emerged beyond which the risk of fracture began to increase. During the process of pancreatic lipolysis, vitamin K dissolves into micelles along with bile salts, thus facilitating its absorption in the proximal intestine. Oral absorption of vitamin K fluctuates both between different individuals and within the same individual, with bioavailability ranging from 10% to 63% (9).

Nanoemulsions: Innovation and Stability

Recently, lipid-based drug formulations have been investigated as a promising approach to increase the absorption of lipophilic drugs. This strategy involves incorporating active ingredients into inert lipid carriers, such as liposomes, lipid nanocarriers, and micro- and nanoemulsions (10). Nanoemulsions, also known as mini-emulsions, are heterogeneous systems in which tiny droplets of an immiscible liquid (dispersed phase) are dispersed in another liquid (continuous phase), typically with sizes ranging from 50 to 500 nm, and in many cases less than 100 nm. They are formed by mixing an oily phase with an aqueous phase in the presence of an emulsifier, which initially leads to the creation of macroemulsions, subsequently reduced to nanodroplets (11). This process does not occur spontaneously and requires an energy input (Tadros et al., 2004). The emulsifier is crucial for reducing interfacial tension and stabilising the droplets, preventing them from merging due to its amphiphilic structure (12,13). Nanoemulsions offer numerous advantages over conventional emulsions and microemulsions. They are significantly more kinetically stable, resisting phase separation for longer periods due to the small droplet size, which hinders phenomena like sedimentation and flocculation (14). Their transparency, due to the droplet size being smaller than the wavelength of visible light, makes them suitable for products requiring optical clarity (15). Their preparation requires lower surfactant concentrations, improving biocompatibility, and they are more resistant to physicochemical changes compared to microemulsions (14). Further advantages include low droplet polydispersity and improved bioavailability of the encapsulated compounds (16). Although thermodynamically unstable (non-spontaneous), they are kinetically stable for extended periods, allowing for greater flexibility in functionalisation (17). The stability of a nanoemulsion is its ability to maintain its physicochemical properties and droplet size unchanged over time, despite being kinetically stable in a non-equilibrium state (18). Stability improves with decreasing droplet size, which reduces mutual attraction and coalescence (12). Separation primarily occurs through Ostwald ripening. Several factors influence stability, including composition (type and concentration of emulsifier, water-to-oil ratio), polydispersity index, physicochemical properties of the components, and temperature (14). The choice of emulsifier is crucial: Ionic ones are stabilised by electrostatic repulsion, while non-ionic ones are stabilised by steric hindrance. The HLB (hydrophilic-lipophilic balance) indicates the emulsifier's affinity between the phases, but the HLD (hydrophilic-lipophilic difference) provides a more precise measurement. The emulsifier concentration is critical, with high concentrations sometimes reducing stability (19). Temperature, ionic strength, pH, and the viscosity of the continuous phase are other influencing factors (20). Stability can be improved by increasing the viscosity of the continuous phase and reducing the dispersed/continuous phase volume ratio and the polydispersity index. Preparation methods are divided into two categories:

- High-energy methods: They apply strong shearing forces. Examples include high-pressure valve homogenisation (HPVH), which produces droplets smaller than 1 nm (21), microfluidization, which fragments droplets in microchannels (22), and ultrasound, which generates acoustic cavitation (23,24). These methods are versatile but can be expensive and damaging to thermosensitive compounds (25).
- Low-energy methods: They exploit changes in the chemical potential of the emulsion components, induced by variations in temperature or composition. These include the phase inversion temperature (PIT) method, which modifies the emulsifier's properties with temperature (19, 26); the phase inversion composition method (PIC), which varies the proportions at a constant temperature (27); self-nanoemulsification, which occurs through solvent diffusion (Anton et al., 2009); the solvent displacement method (28); and the bubble bursting method, which utilises the rupture of gas bubbles (29). Low-energy methods are limited by their compositional specificity (30).

Advantages of Vitamin K SNELTs

The multiple advantages of formulating vitamin K in nanoemulsions, particularly in the form of self-nanoemulsifying lyophilised tablets (SNELTs), represent an innovative strategy to overcome the limitations of conventional formulations (9). One of the main problems with vitamin K is its limited solubility, which leads to low oral bioavailability and wide inter-individual variability (31,32). SNELTs effectively overcome this limitation, significantly improving both the speed and extent of vitamin K absorption. Clinical results in healthy volunteers demonstrated a significant increase in relative bioavailability (169.67%) compared to commercial oral tablets, as well as significantly higher area under the curve (AUC) and maximum plasma concentration (Cmax). It is interesting to note that the AUC of SNELTs showed no significant

differences compared to commercial intramuscular injection, positioning them as a highly effective oral alternative (9). This improvement is attributable to the ability of nanoemulsions to increase surface area, enhance the drug's solvent capacity, and optimise permeation through biological membranes, promoting lymphatic transport (33,34). SNEDDS systems, of which SNELTs are a form, help improve in situ drug solubilisation, bypass first-pass hepatic metabolism, inhibit cellular efflux mechanisms, and protect the drug from degradation in the gastrointestinal tract (35,36). SNELTs also demonstrate a marked superiority in drug release and in vitro dissolution, with over 80% of the drug released within 30 minutes, a significantly better result compared to the 28% released by commercial tablets after 60 minutes. This is facilitated by the freeze-dried form of the tablets, which creates a three-dimensional porous polymer structure with a high surface area, promoting rapid disintegration, rehydration, and solubilisation in saliva, eliminating the need for water or chewing (9). SNELTs produce the "smallest and most stable" nanoemulsion globules, and the nanoemulsions thus formed are robust to dilution, showing no phase separation or drug precipitation even after 24 hours of storage. As a solid dosage form, SNELTs offer inherent advantages in terms of stability, excellent preservation, and ease of handling (37-39). Additionally, the tablets showed good drug content uniformity (>95%), friability resistance, and improved mechanical properties.

Characterisation and Culture of Primary Osteoblasts with Vitamin K Nanoparticles

The objective of this article is to evaluate the influence of nanoemulsions on the regeneration and differentiation of osteoblastic cells on an SLA-treated titanium surface. Understanding and optimising implant surfaces, both through their bioactivation to improve wettability () and through effective decontamination using various methodologies such as ultrasonic scaling or air-abrasive powders, are crucial aspects for the long-term success of osseointegration (40). In this context, new methodologies, including in implantology, represent innovative approaches for proper bone regeneration (41,42). Advanced cell biology and microscopy methodologies were employed for the characterisation of primary osteoblast cultures and the study of their interaction with vitamin K nanoparticles. The expression of the transcription factor RUNX2 was analysed by immunocytochemistry on fixed and pretreated cell samples, using an anti-RUNX2 monoclonal antibody and an HRP-DAB detection system, highlighting the crucial role of this marker in osteogenic differentiation, a process widely studied in various cell sources (43). The images were acquired with an optical microscope at 20× magnification. Primary cultures of human osteoblasts were obtained from trabecular bone fragments collected during hip arthroplasty procedures, following enzymatic digestion protocols. The cells were cultured in specific medium, maintained at 37°C and 5% CO2, and seeded onto plates for subsequent experimentation. To evaluate growth and adhesion, primary osteoblasts from osteoporotic patients were cultured on sterilised titanium discs. On these discs, cells were deposited and treated with a nanoemulsion of vitamin K nanoparticles at different concentrations (100, 50, 25 microgrammes). After 7 days of culture, with periodic medium changes, the cells were fixed for electron microscopy analysis. The selected samples, particularly those treated with 100 nM nanoK, which showed increased responsiveness, were dehydrated and metallized for scanning electron microscopy (SEM) analysis. Elemental chemical analysis (EDS) was performed on different areas of the discs to identify surface anomalies and mineralisations, allowing for the mapping of key elements like Calcium (Ca) to understand cellular behaviour in the presence of vitamin K.

Interaction of Vitamin K Nanoparticles with Osteoblasts

This study investigated the interaction between primary osteoblasts and titanium surfaces in the presence of Vitamin K nanoparticles. Scanning electron microscopy (SEM) analysis revealed that osteoblasts treated with Vitamin K nanoparticles showed significantly improved cell adhesion and organisation on the titanium surface compared to controls. Specifically, marked osteoblast overgrowth and an increased predisposition to mineralisation were observed in the treated samples, suggesting enhanced osseointegration. Energy-dispersive X-ray spectroscopy (EDS) further supported these findings, highlighting an increased availability of Calcium (Ca) atoms in the Vitamin K-treated samples, indicating a more effective ossification process (44). These results confirm the tendency of Vitamin K nanoparticles to improve cellular adhesion and mineralisation, a crucial factor for osseointegration in low bone density contexts such as osteoporosis (45). These results, which highlight an improvement in osteoblast activity on titanium surfaces, are in line with research demonstrating how the microtopography of dental implants positively influences osteoblast proliferation and bone deposition. (46). By improving the bioavailability of Vitamin K, which is essential for bone metabolism (16), this nanotechnology approach suggests promising potential for clinical application in prosthetic rehabilitation. Although this preliminary study provides a solid foundation, further in vitro and in vivo research is needed to fully confirm its efficacy in humans.

CONCLUSIONS

This study explored the potential of vitamin K nanoemulsions as an innovative strategy to enhance the regeneration and differentiation of osteoblastic cells on titanium surfaces. This research falls within the broader context of efforts to optimise bone regeneration on titanium structures, as demonstrated by the use of titanium-reinforced membranes for horizontal guided bone regeneration (47). Starting from the recognised importance of vitamin K for bone and dental health – highlighted by its role in the synthesis of proteins like osteocalcin, essential for binding calcium and promoting strong and healthy structures – the article addressed the challenges related to the poor and variable oral bioavailability of vitamin K itself. Our results clearly demonstrated that the vitamin K formulation in nanoparticles is able to overcome these limitations, promoting significantly improved cellular adhesion and organisation of human primary osteoblasts on titanium surfaces. Scanning electron microscopy (SEM) and energy-dispersive spectroscopy (EDS) analyses revealed marked cellular hyperconfluence and an increased predisposition to mineralisation, with a significant increase in calcium content in the treated samples. These data confirm that the nanotechnological approach, through the optimisation of vitamin K bioavailability, actively improves crucial processes for osseointegration, particularly in low bone density contexts such as osteoporosis. These findings contribute to the vast and dynamic field of bone regeneration, which sees extensive exploration of materials and techniques, including bone adhesives, for various clinical applications (48). Self-nanoemulsifying lyophilised tablets (SNELTs) of vitamin K therefore represent a promising solution for improving therapeutic efficacy and prosthetic rehabilitation. The resulting optimisation of osseointegration has the potential to significantly contribute to the long-term success of implants, improving the survival rate even in regenerated sites, as highlighted in studies examining the impact of innovative biomaterials (49) or advanced surgical techniques (50). Although this preliminary study provides a solid foundation for future applications, further in vitro and in vivo research is needed to fully confirm efficacy in humans and translate these promising results into tangible clinical benefits. It is evident that research in this field is constantly evolving, and the results obtained demonstrate the effectiveness derived from the use of new materials and innovative techniques (51-53).

Conflict of interest

The authors declare that they have no conflict of interest.

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TOTAL EDENTULISM AND COGNITIVE DECLINE: ANALYSIS OF NEUROPHYSIOLOGICAL MECHANISMS AND BENEFITS OF IMPLANT-SUPPORTED REHABILITATION

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ABSTRACT

Introduction: Total edentulism, characterized by the complete loss of teeth, significantly impacts the quality of life in older adults, leading to health inequalities. It is associated with oral health deterioration, masticatory dysfunction, and an emerging connection to cognitive decline through neurophysiological mechanisms. *Materials and Methods:* A review of the literature was conducted using databases such as PubMed, Embase, Cochrane Library, Scopus, and Web of Science. The search terms were focused on "edentulism," "cognitive decline," and "implant-supported rehabilitation." Study selection involved two independent reviewers, with disagreements resolved by a third reviewer and quality assessments conducted using established tools. *Discussion:* The prevalence of edentulism is increasing, and it carries multifaceted health implications, including a link to cognitive decline associated with the loss of occlusal support. Evidence suggests that improved oral health through implant-supported solutions enhances masticatory function, cerebral blood flow, and neurofunctional outcomes compared to complete dentures. Techniques such as fMRI and NIRS demonstrate how these rehabilitative approaches positively affect brain regions critical for cognitive functions. *Conclusions:* The findings support the idea that implant-supported rehabilitation not only restores oral function but may also mitigate cognitive decline in edentulous patients. Comprehensive treatment planning, considering anatomical, functional, and socioeconomic factors, is essential. Future research should focus on longitudinal studies to better establish causal relationships and develop clinical guidelines aimed at optimizing outcomes for edentulous individuals.

KEYWORDS: *Edentulism, cognitive decline, implant-supported rehabilitation, masticatory function, neurophysiological mechanisms*

INTRODUCTION

Total edentulism, defined as the complete loss of teeth, is the final outcome of untreated oral pathological processes (caries, periodontal disease) and iatrogenic factors, trauma, and genetic predisposition (1,2). With the ageing population, its prevalence is increasing, with significant impacts on the quality of life of older adults and on health inequalities related to socioeconomic factors and access to care (3,4). In addition to local changes – alveolar resorption, loss of perioral support, reduction in vertical dimension, and accentuation of facial ageing signs – edentulism compromises masticatory function and nutrition (5-7). Numerous studies indicate a correlation between tooth loss, reduced chewing activity, and cognitive decline: The loss of occlusal support has been associated with an increased risk of neurodegenerative diseases

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and cognitive decline (8-10). The proposed mechanisms involve changes in cerebral blood flow and cortical activation in areas such as the prefrontal cortex, hippocampus, thalamus, cerebellum, and basal ganglia, as well as alterations in functional connectivity detectable with fMRI and neuroimaging studies (11-15). Reduced chewing leads to decreased perfusion and oxygenation in critical regions for learning and memory, contributing to the risk of cognitive decline (11,16). Prosthetic rehabilitation, particularly implant-supported solutions, not only restores aesthetics and masticatory function but also shows documented neurofunctional benefits with fMRI and near-infrared techniques (7, 17-19). Comparative studies report increased activation of the hippocampus, prefrontal cortex, and other cognitive areas, as well as improvements in neuropsychological tests (MMSE, 3MS, QMCI, DST, HSC, TMT) in patients treated with implant-supported prostheses compared to complete dentures or edentulous conditions (7,17,20,21). The choice of therapy – removable complete dentures, overdentures, or fixed restorations like All-on-4 or a Toronto Bridge – depends on anatomical conditions, functional needs, economic resources, and surgical risks (22-25). Techniques like All-on-4 and Toronto Bridge allow for fixed rehabilitations with biomechanical advantages, although they require risk assessment and planning (24,26). This article aims to review the evidence on the impact of edentulism on overall and cognitive health, analyse the neurophysiological mechanisms related to mastication, and evaluate the clinical and cerebral benefits of different implant-supported prosthetic rehabilitation strategies, with the objective of providing guidance for optimising functional, aesthetic, and cognitive outcomes in edentulous patients (1,7,17).

MATERIALS AND METHODS

Review of the literature on edentulism, masticatory function, cognitive decline, and implant-supported rehabilitation.

- Databases queried: PubMed/MEDLINE, Embase, Cochrane Library, Scopus, Web of Science.
- Research period: until 01/25/2026.
- Search terms (Boolean combinations): "edentulism" OR "edentulia" AND "mastication" OR "chewing" AND "cognitive decline" OR "dementia" OR "memory" AND "implant-supported prosthesis" OR "All-on-4" OR "overdenture" AND "fMRI" OR "NIRS" OR "near-infrared" OR "neuroimaging". Adapted strategy for each database; manual search of the bibliographies of the selected articles and relevant reviews.
- Selection and Extraction: two independent reviewers; resolution of disagreements by a third reviewer; Quality assessment using appropriate tools (e.g., Cochrane RoB, Newcastle-Ottawa Scale).

DISCUSSION

Edentulism and its Health Implications

Total edentulism is the loss of all teeth, and it is usually the endpoint of a history of oral diseases (WHO - ORAL HEALTH). The causes of edentulism are complex; the main ones are the final stage of untreated caries and the final stage of periodontal disease (1). The correlation between edentulism and individuals' genetic profiles is also important, and finally, it can be the consequence of iatrogenic, traumatic, or therapeutic causes (2). Literature data indicate that approximately 80% of elderly people suffer from edentulism, a condition that can have repercussions in other body districts, dangerously compromising the health status of other organs (4). Due to the ageing population, and consequently the increase in the number of elderly people, edentulism is constantly growing (3). An important observation is regarding the number of people who completely replace missing teeth with dental implants or simple dentures, which is decreasing, especially among the older population. Since edentulism is a consequence of oral diseases, access to dental care and prevention are important. It is known that oral complications such as mucositis can negatively impact the course of treatment. A promising treatment for oral mucositis is the use of platelet-rich fibrin (27,28). This condition can compromise not only oral health but also the long-term success of the prosthesis. Studies have shown that periodontal treatment, even in combination with therapies like low-intensity laser therapy, can positively influence gingival inflammation levels (29). Oral health, prevention, and access to care differ across the population based on social differences, which are less pronounced in individuals with low education or limited financial resources. Edentulism leads to centripetal resorption of the alveolar processes (5), resulting in reduced support and stretching of the perioral tissues, accentuating the typical signs of ageing: wrinkles, skin laxity, reduced tone, reduced intermaxillary vertical dimension, and mandibular prognathism (6).

Edentulism and Cognitive Decline

The ageing population brings with it not only an increase in cases of total edentulism, but also cognitive decline that can profoundly affect the quality of life of older individuals (30). In addition to the normal cognitive decline that occurs

physiologically with age, neurodegenerative diseases like Alzheimer's disease (AD) and mild cognitive impairment (MCI) can develop, increasing the risk of isolation and impairment in daily activities (10,31). It has been demonstrated that there is a bidirectional relationship between cognitive dysfunction and loss of occlusal support, with tooth loss emerging as a potential risk factor for the onset of neurodegenerative diseases (8,9). People with cognitive impairments are often more dependent on others, not only for their oral hygiene care but also for managing their daily activities; This increases their predisposition to neglect their oral health. Indeed, the presence of edentulism can further exacerbate cognitive decline due to mechanisms such as decreased chewing, which in turn affects the activation of specific brain areas involved in learning and memory processes (16). Some studies have indicated that active chewing stimulates crucial brain regions, leading to increased blood flow to vital areas like the prefrontal cortex and hippocampus, which are essential for maintaining cognitive functions (11,12). One method for evaluating brain functional connectivity is fMRI. Studies conducted using this examination show that the act of chewing produces bilateral functional connections between the motor cortices (13). Furthermore, the seed regions (starting points of interest in fMRI, whose neurological connections with other structures are to be evaluated) in the motor cortex, in turn, show bilateral functional connections with other areas: the posterior cerebellar lobes, precuneus, cuneus, and cingulate cortex. Both cerebellar hemispheres have functional connection circuits between them (32). During chewing, the most activated regions are the prefrontal cortex, the caudate nucleus, and the thalamus (14). The presence of a correlation between the intensity of the chewing act and blood perfusion in the trigeminal main nucleus is important, as it determines an increase in neuronal activity (15). Chewing has a beneficial effect on oxygenation in the prefrontal cortex (PFC) and hippocampus, where high levels of oxygen, necessary for learning and memory processes, have been detected (33). Increases in oxygenation related to chewing have also been observed in the sensorimotor cortex, supplementary motor area, thalamus, cerebellum, and insula (34). These regions are also associated with learning and memory, and consequently, the increase in oxygen is favourable as it is fundamental for the execution of these processes (11). The reduction in chewing ability following tooth loss can therefore compromise these functions and increase the risk of developing more severe forms of dementia. A thorough analysis of the literature suggests that improving oral health through implant-supported rehabilitation not only offers aesthetic and functional benefits but could also serve as a preventive intervention to mitigate cognitive decline (32).

Brain effects of prosthetic rehabilitation

Rehabilitation through the use of dental prostheses undoubtedly improves oral health, as it restores chewing function, improves swallowing and consequently nutrition, and restores or enhances facial aesthetics (7), supported by precise digital techniques (35). The brain-level advantages of using implant-supported prostheses compared to complete dentures and edentulism have been highlighted using different techniques and methods. Functional Magnetic Resonance Imaging (fMRI) is preferred for assessing brain activity; This molecular imaging technique allows for the detection of changes related to cerebral blood flow using paramagnetic iron as a contrast agent, demonstrating regional and temporal variations in brain metabolism and representing neuronal activity through Blood Oxygenation Level Dependent (BOLD) signals. It is interesting to associate fMRI of chewing tests and memory recall tests, during which patients are asked to remember three random words assigned to them, with the Mini-Mental State Examination Test (MMSE), in which they are asked questions to assess their visuospatial skills, orientation, memory, attention, and language. In studies conducted using this approach, fMRI and MMSE were performed in three different situations: edentulous condition, with complete dentures, and with implant-supported prostheses (17):

1. In the chewing test using implant-supported prostheses, the highest activation was observed in the insula, less in the prefrontal cortex and hippocampus, unlike the use of complete dentures and the edentulous condition. This is because complete dentures are characterised by greater mobility, which results in an unstable and irregular chewing pattern, unlike implant-supported prostheses, which allow for a function similar to that performed with natural teeth (18). The use of prostheses on implants has led to a smaller number of activation areas compared to the use of complete dentures or in edentulous conditions, which is attributed to mastication performed with the basal tissues. The activation of the sensorimotor cortex, recorded in these tests, is attributable to modelling, bolus repositioning, and modulation of masticatory movements (36). Thalamic activation was observed with both prostheses.
2. The memory recall test showed statistically significant increased activation of the hippocampus and prefrontal cortex with the use of implant-supported prostheses. The hippocampus is responsible for the retrieval and consolidation of episodic memory. Furthermore, the activation of the parietal lobe, which is associated with memory and learning (20), the cerebellum, which can potentially participate in a neurological network that initiates and monitors the conscious retrieval of episodic memory (21), and the thalamus, which is involved in

thalamocortical circuits that play integrative roles in memory, cognition, and recall or retrieval processes, was also found in the sole use of the prosthesis on implants.

3. MMSE tests yielded higher scores in patients with implant-supported prostheses, with statistically significant differences, suggesting greater brain function, consistent with the results obtained from fMRI, which showed that during the recall test, a greater number of brain areas were active for implant-supported prostheses compared to complete dentures, suggesting that treatment with implant-supported prostheses can potentially enhance the functioning of brain areas involved in memory and recall (19).

It is equally significant to combine fMRI with the execution of cognitive activation tasks such as (Tan D. et al.): The Continuous Performance Test (CPT), in which 120 yellow or white letters (B, C, D, or G) are presented in sequence and patients must press buttons when the same yellow letter appears twice in a row, and the Go/No-Go task, which displays the word "press" in green for a "Go" response or red for a "NoGo" response, requires patients to respond by pressing the green button for "Go" stimuli and not responding for "NoGo" stimuli. These determine the activation of brain areas, during which fMRI is performed with BOLD signal recording and subsequent contrast image acquisition (7). Thanks to this combined approach, it is highlighted that the transition from complete dentures to implant-supported prostheses has several advantages. Implant-supported prostheses offer better chewing performance compared to complete dentures within 12 months, a period during which adaptive modifications are continuously implemented, leading to improvements in chewing performance. Specifically, the Continuous Performance Test (CPT) results show that in the first week after loading, prostheses on implants are associated with a reduction in cortical activation in the right and left dorsolateral prefrontal cortex, right and left superior parietal cortex, right and left inferior parietal cortex, and dorsal anterior cingulate cortex, compared to the activation observed with complete dentures. At six weeks after implant-supported rehabilitation, there is an increase in cortical activation in all areas except the left superior parietal cortex and the left inferior parietal cortex. Among the tests for neurocognitive assessment to be correlated with fMRI exams, we can mention (7):

- Modified Mini-Mental State Examination (3MS), an extension of the MMSE, used for screening for dementia or severe cognitive impairment. This test examines attention, memory, and executive functions.
- Quick Mild Cognitive Impairment (QMCI), to distinguish between mild cognitive impairment, normal cognitive status, and dementia, corrected for age and education. Assess visuospatial function, logical memory, and verbal fluency.
- Wechsler Adult Intelligence Scale - 4th Edition (WAIS-IV) - Digit Span Task (DST), which is divided into Digit Forward, which assesses auditory attention, and Digit Backward, which assesses working memory.
- Hayling Sentence Completion (HSC), which assesses initiation speed and inhibitory control through sentence completion.
- Trail Making Test (TMT), which has 2 versions: "A" where you have to connect 25 circled numbers on a piece of paper; "B" where you have to alternate letters and numbers in ascending order.

Prostheses on implants, in the first week of loading, are associated with a reduction in neurocognitive function, assessed using the 3MS, QMCI, DST, and HSC tests, while an improvement is observed at the sixth week, with HSC test results even increasing up to 12 months. The first stage of neurocognitive decline can be attributed to emotional stress, physical trauma during implant placement, and the pain and discomfort experienced in the postoperative phase. Postoperative nociceptive stimuli can affect neurocognitive abilities as they can reduce the afferent feedback to the CNS that is necessary for higher cognitive functions (37). The return to baseline or higher values of cognitive functions is observed after 6 weeks, a period characterised by the absence of nociceptive symptoms and increased masticatory performance (7).

A significant technique for analysing the benefits of prosthetics is multi-channel near-infrared optical topography. This mode allows for the assessment of blood volume and oxygen saturation in the brain in response to brain activation, recording neuronal activity through 24 channels (12 on the right and 12 on the left) placed on the scalp, each covering a portion of the underlying cortex. The system uses a light source to generate a laser beam with wavelengths of 780 and 830 nm, directed towards the patient's head via optical fibres. The reflected light is received by photodiode detectors, and a controller converts the optical signal into an electrical signal for further processing. This non-invasive technique allows for the estimation of changes in the concentrations of oxygenated haemoglobin (Oxy-Hb), deoxygenated haemoglobin (Deoxy-Hb), and total haemoglobin (Total-Hb) (38). Thanks to this technology, they have demonstrated that implant-supported rehabilitation increases blood volume in the brain. Neuronal activity was assessed in patients with prostheses on implants during maximum clenching tasks. The measurements were conducted by alternating 30 seconds of rest with 10 seconds of maximum grip, repeated five times. Maximum and minimum Total-Hb concentrations were measured for each channel, and the haemodynamic responses between patients with and without prostheses were compared, including the latency to maximum blood volume after clamping. The results indicate a localised increase in total haemoglobin

concentration in the cortex during the clamping test. With the use of prostheses on implants, the increase in cerebral blood flow is significantly higher compared to subjects without prostheses, although the latency of blood flow to maximum Total-Hb concentration was not statistically significant after maximum tightening.

Prosthetic rehabilitation and cognitive functions

Removable complete dentures are the most common prosthetic rehabilitation solution in cases of economic limitations (22,23). Some distinguishing features are the low retention and stability, which are particularly noticeable in the mandible. These issues significantly compromise masticatory function, leading to functional limitations with negative impacts on quality of life (39,40). The usual protocol for the rehabilitation of edentulous patients involves overdentures to improve prosthesis retention and stability, allowing forces to act in a way that favours masticatory function (41). The choice of the type of rehabilitation, whether fixed or removable, depends on the number and distribution of implants, the morphology of the residual ridge, aesthetic outcomes, and the hygiene protocol (42). Tooth loss and the long-term use of complete dentures can lead to bone atrophy in the lower jaw, causing the nerve to become superficial, resulting in pain and discomfort during chewing. In the upper arch, the loss of teeth is associated with the pneumatization of the maxillary sinus. When dealing with atrophic mandibles, the biggest difficulty lies in the proximity of the mandibular nerve. Bone grafts can be a regenerative solution to increase bone volume (43). In the upper jaw, atrophy primarily affects the posterior sectors (44), where the main focus should be on the position of the maxillary sinus; If adequate bone volume restoration is needed for fixture placement, the solution is a maxillary sinus lift procedure. Recent studies have shown that the use of innovative biomaterials for bone regeneration has led to satisfactory implant survival rates (45). Other research has explored the use of mesenchymal stem cells from adipose tissue and dental pulp to achieve osteogenic differentiation, suggesting further opportunities to enhance bone regeneration (46). Based on the above considerations, the concept of "All-on-4" is now widespread: a fixed implant-supported rehabilitation using four immediately loaded implants. The implant placement site is in the anterior region, two axially and two distally with a posterior inclination between 30 and 45 degrees (47). In the Branemark protocol, where implants were placed axially, cantilevers up to 20 mm were generated, leading to high stresses and bending on the implants and the surrounding bone, increasing marginal bone resorption and affecting implant survival (48). All-on-4 rehabilitation offers several advantages: allows for the use of longer implants, a larger contact area between the implant and the bone, greater primary stability (49) thanks to the possibility of achieving bicorticalism, and the immediate loading of acrylic resin prostheses while maintaining aesthetics and function; Reduced costs; reduced time, less need for bone grafts due to the possibility of utilising all available bone (24, 50), lower morbidity, no differences in survival rates compared to axially placed implants (26, 51), and finally, increasing the distance between implants and reducing the cantilever length provides biomechanical advantages with better distribution of masticatory forces (25). Another type of fixed rehabilitation is the Toronto Bridge, which utilises 4/6 implants placed in the intraforaminal area with 2 suspended elements distally. The prosthetic component is capable of replacing lost tissues, compensating for atrophy; It allows for the recovery of vertical dimension and resolves any intermaxillary discrepancies. The ample space between the prosthesis and the underlying ridge allows the patient to perform adequate home oral hygiene manoeuvres. The evidence therefore suggests that the adoption of these methodologies has led to positive results. Innovative techniques in the field of implant surgery are fundamental for improving clinical outcomes and patient satisfaction (52-54).

CONCLUSIONS

Total edentulism is a widespread and growing condition in the elderly population, with multidimensional impacts that extend beyond the oral sphere: chewing impairment, nutritional decline, aesthetic alterations, and increasingly supported by evidence, an association with cognitive decline through neurophysiological mechanisms related to reduced masticatory stimulation and changes in cerebral blood flow. Functional imaging techniques (fMRI, NIRS) have documented how chewing and implant-supported rehabilitation modulate the activation and perfusion of brain regions critical for memory and executive functions (prefrontal cortex, hippocampus, thalamus, cerebellum), and how implant-supported prostheses tend to yield better neurofunctional outcomes compared to removable complete dentures. From a clinical perspective, the therapeutic choice must balance anatomical, functional, economic, and surgical risk factors: Overdentures and fixed solutions (All-on-4, Toronto Bridge) offer effective options for improving retention, stability, and masticatory performance, with potential positive impacts on cognitive function and quality of life. It is essential that implant-supported rehabilitation is performed correctly; Naturally, the cleanliness and condition of the implant surfaces determine the success of the rehabilitation and should be an integral part of treatment decisions and postoperative care. (55-59). However, an individual and multidisciplinary assessment is necessary, as well as careful information for the patient about the expected benefits and possible risks. Further longitudinal and systematic studies with rigorous designs and large

samples are needed to consolidate the causal relationship between prosthetic rehabilitation and cognitive improvement, define the underlying mechanisms, and establish clinical guidelines aimed at preventing cognitive decline through oral health interventions. Meanwhile, promoting prevention, access to dental care, and the timely adoption of appropriate rehabilitation strategies represent pragmatic measures to reduce the functional, aesthetic, and potentially neurocognitive burden of edentulism.

Conflict of interest

The authors declare that they have no conflict of interest.

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