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Concept of Transmucosal Biological Complex and Its Clinical Implications in Dental Implantology

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Concept of Transmucosal Biological Complex and Its Clinical Implications in Dental Implantology

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Abstract

Dental implant rehabilitation has become the first-line treatment option for dentition defect and edentulism, and the transmucosal area is the core region affecting the long-term stability of implant rehabilitation. Previous research in this field has been mostly limited to a single histological or structural perspective. This paper innovatively proposes the concept of the Transmucosal Biological Complex (TBC), which integrates implant components (implant neck, abutment, and transmucosal part of the restoration) above the bone level and below the gingival margin with the surrounding hard and soft tissues as an integrated research object. By comprehensively reviewing the latest literature in the field of dental implantation, this paper expounds the composition system of the TBC, and systematically explores its key influencing factors, including implant neck design, type and stability of the implant-abutment connection, transmucosal materials of abutments/restorations, peri-implant soft tissue phenotype, and transmucosal design of the superstructure. For each influencing factor, the paper objectively clarifies its mechanism of action on the peri-implant marginal bone and soft tissues, and details its clinical advantages, application limitations, and existing research controversies in the field. This study aims to provide in-depth reference and guidance for clinical decision-making, technical application and scientific research in dental implantation, and to help improve the long-term clinical outcomes of implant rehabilitation and patients' quality of life.

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1. Introduction

Dental implant rehabilitation for the restoration of missing teeth has been increasingly accepted by patients and has become the preferred treatment for tooth loss. Taking implant treatment for single tooth loss as an example, after the completion of implant rehabilitation, the entire intraoral implant restoration (implant + abutment + restoration) can be divided into three parts: the supragingival part, i.e., the restoration part above the gingiva; the transmucosal area, i.e., the range from below the gingival margin to the bone level, including the implant abutment part, soft tissues and part of the subgingival restoration; and the endosseous part, where osseointegration occurs between the implant and the jawbone. This classification helps clinicians analyze the effects of influencing factors of each part on the long-term outcomes of implantation. This paper focuses on the composition of the second part, the transmucosal area, analyzes various factors affecting the long-term stability of peri-implant marginal bone and soft tissues, and proposes the concept of the Transmucosal Biological Complex (TBC).

In the early stage, scholars used terms such as biologic width [1], supracrestal tissue attachment [2], and Implant Supracrestal Complex (ISC) [3] to describe the peri-implant tissues above the marginal bone. Among them, the biologic width only focuses on the histological attachment dimension of soft tissues, and the supracrestal tissue attachment emphasizes the structural description of soft tissues from the alveolar crest to the epithelial attachment. The concept of the Implant Supracrestal Complex (ISC) was proposed in 2021, with its core components elaborated [3]. Although the content of this paper is similar to it, the TBC not only updates the latest literature

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evidence but also focuses on the integration of all peri-implant hard and soft tissues and implant components above the bone level and below the gingival margin into an organic whole. In terms of composition, the TBC mainly includes implant neck design, type and stability of the implant-abutment connection, transmucosal materials of abutments/restorations, peri-implant soft tissue phenotype, and transmucosal design of the superstructure. By analyzing the synergistic effects of different factors on peri-implant soft tissues and marginal bone, this paper clarifies the core value of this region in the clinical diagnosis and treatment of implant rehabilitation, and provides a new idea for the holistic evaluation and design of implant rehabilitation.

2. Components of the Transmucosal Biological Complex

2.1. Implant Neck Design

The earliest Branemark implant system adopted an external connection abutment design, which was inevitably accompanied by marginal bone resorption one year after functional loading [4–8]. Meanwhile, tissue-level implants were proposed and proven to have advantages in marginal bone stability [9]. This paper mainly discusses the effects of the most common clinical implant neck designs (platform switching, cervical micro-thread design, cervical surface roughness, and smooth collar design) on marginal bone and soft tissues.

2.1.1. Platform Switching Design

Platform switching is an important innovative concept in implant neck design, whose core is to design the abutment diameter smaller than the platform diameter to achieve horizontal inward transfer of the microgap [10]. This design can effectively reduce marginal bone resorption at the implant neck, and its mechanism of action is reflected in two aspects: first, the microgap is transferred from the edge of the implant neck to the inside of the implant, reducing the stimulation of marginal bone by bacterial aggregation and inflammatory reactions at the microgap [11]; second, it changes the stress distribution at the implant neck, shifting the stress concentration area to the deep part of the implant and reducing the stress on the marginal bone, thereby decreasing bone resorption [12,13]. More than 30 clinical studies and more than ten long-term follow-up studies (5-10 years of follow-up) have shown that the amount of marginal bone resorption of implants with platform switching design is significantly lower than that of traditional implants [14]. For example, a study including 58 patients found that after 10 years, implants with platform switching (PS) had lower values of marginal bone loss (MBL) and probing pocket depth (PPD), and higher pink esthetic score (PES) compared with implants with platform matching (PM), with statistical significance [15]. In addition, the platform switching design can promote the stability of peri-implant soft tissues, increase soft tissue attachment, and improve the esthetic effect of implant rehabilitation [16–18].

2.1.2. Implant Cervical Roughness

To preserve the bone at the alveolar crest, improve the long-term success rate of implant treatment and achieve an ideal esthetic effect, researchers have proposed a variety of macro and micro design improvement schemes for implants to improve the effect of marginal bone maintenance [19–21]. Combined with clinical experience, different implant systems on the market may experience varying degrees of marginal bone resorption, which is related to multiple factors [22–25]. When the cervical bone is resorbed, the cervical surface of the implant is exposed, and the cervical rough surface design then becomes an important strategy to improve the stability of the TBC. Literature has pointed out that the exposure of the rough surface of implants will have an adverse effect on plaque control, while the micro-rough surface has sufficient long-term clinical evidence in plaque control [26], which can not only reduce the risk of peri-implantitis [27–29] but also affect the biological behavior of peri-implant soft tissues, promote the attachment and growth of soft tissue cells on the implant surface, form a tighter soft tissue seal, effectively block bacterial invasion of the implant-bone interface, and

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provide a stable barrier for the TBC [30]. A systematic review evaluating the survival rate and MBL of implants with different surface roughness for 10 years or more found that the survival rate of all implants during the functional period of 10 years or more reached 82.9%-100%, with an average MBL of less than 2.0 mm; the turned surface had the smallest MBL, the moderately rough surface had a higher survival rate; the roughest titanium plasma-sprayed (TPS) surface had the highest failure probability, and the anodised surface had the lowest failure probability [31].

Finite element analysis studies have shown that the implant cervical micro-thread design can better distribute stress to the surrounding bone tissue and may reduce MBL [32], but the clinical effect of this design is still controversial [33,34]. A recent systematic review showed no significant difference in marginal bone resorption between implants with cervical micro-threads and conventional rough cervical implants [35]. Hoori Aslroosta et al. also found that the micro-thread design had no more advantages than the ordinary thread design in preserving marginal bone of immediately placed implants during the 5-year loading period [36]. The long-term clinical evidence for the improvement of marginal bone resorption by the cervical micro-thread design is insufficient, and large-sample, multi-center studies with unified standards are still needed for verification.

2.2. Implant-Abutment Connection Type and Stability

The implant-abutment connection structure is one of the core designs to ensure the stability, adaptability and long service life of the restoration in dental implant rehabilitation. Its classification is mainly based on the interface morphology, anti-rotation structure and retention method of the implant and abutment. The current mainstream connection structures are internal and external connections. External connections usually have an external hexagon structure on the implant platform, while internal connections can be subdivided into internal hexagon, internal octagon and Morse taper connections [37].

External connection was a common way of early implant-abutment connection, which realizes connection through the convex structure outside the implant and the groove of the abutment. It has a simple structure and easy operation, but the connection part is located outside the implant, which is susceptible to oral bacteria and mechanical stress, leading to an increase in microgap and a higher risk of peri-implantitis. Studies have shown that after long-term use, the microgap at the implant-abutment interface of externally connected implants is significantly larger than that of internally connected implants, and the amount of marginal bone resorption is relatively higher [4–8]. Literature reports that the screw loosening rate of this type of connection is 6%～48% [38], and it is difficult to maintain the preload (the abutment removal torque needs to be 10% lower than the installation torque) [39,40].

With the rapid development of two-stage implant technology, internal connection represented by internal hexagon connection has gradually occupied a larger market share. Internal connection refers to the abutment extending 4～6 mm into the internal cavity of the implant and locking with the implant to form a conical, octagonal, hexagonal, trilobal or splined structure, which can be further divided into tapered connection, butt connection and hybrid connection. Tapered connection is derived from the Morse taper concept in mechanical engineering and is a conical nesting structure, also known as conical connection; the joint surface of the implant and abutment in butt connection has no taper and is only fixed by the retention screw; hybrid connection has both a taper structure and a regular polygonal anti-rotation/guide groove structure. Compared with external connection, internal connection can significantly reduce the rotational freedom and improve mechanical stability; if the internal connection adopts the platform switching design, it can also reduce the stress distribution of the bone tissue around the implant-abutment interface [41–45].

In terms of stability, experimental studies have shown that compared with implants with external hexagon and internal hexagon connections, implants with Morse taper connection have less abutment torque loss and can better maintain a tight connection between the abutment and the implant [46]. In addition, the geometric structure of the implant-abutment connection significantly affects the torque loss under cyclic loading; the external hexagon connection is the most sensitive to

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preload loss, and the Morse taper and conical designs have better stability [47]. In terms of sealing, the implant system with Morse taper connection has good microbial sealing performance, which can significantly reduce the microgap at the implant-abutment interface, avoid microbial aggregation and leakage, and reduce marginal bone resorption [48,49]. Clinical studies have found that the incidence of peri-implantitis in implants with Morse taper connection is significantly lower than that in other connection methods during long-term follow-up [50,51].

In clinical practice, some clinicians may choose third-party abutments and screws to reduce costs. However, third-party abutments and screws may have differences in micro-morphology, material properties and processing accuracy from the original components, which will lead to microgaps in the connection area and damage the sealing of the implant-abutment interface. Original abutments and non-original certified abutments are significantly superior to non-original compatible abutments in mechanical results, mechanical strength, microleakage control and marginal accuracy [52,53]. The existence of microgaps not only makes it easy for oral bacteria to invade and cause peri-implantitis, but also leads to uneven stress on the implant neck and increases the risk of marginal bone resorption. In addition, the quality of third-party abutments and screws is uneven, and their mechanical properties and biocompatibility are difficult to guarantee, which may affect the long-term stability of implant rehabilitation [54]. Therefore, to ensure the quality and long-term success of implant rehabilitation, it is recommended to use original abutments and screws, or third-party abutments authorized by original factory data in clinical practice.

2.3. Transmucosal Materials of Abutments/Restorations

The core selection principle of transmucosal materials for abutments/restorations is to balance biocompatibility, mechanical properties and clinical adaptability. At present, the most commonly used clinical materials are titanium and zirconia, each with its own advantages and disadvantages in characteristics and clinical application, which are analyzed below in combination with clinical needs:

2.3.1. Titanium

Titanium is one of the most commonly used materials for the transmucosal area of abutments/restorations. It is widely used in the field of dental implantation due to its good biocompatibility, corrosion resistance and mechanical properties. It can form a good biological combination with peri-implant soft tissues, induce the attachment and growth of soft tissue cells on its surface, and form a stable soft tissue seal [55]. However, its limitations are also obvious: the metallic color of titanium abutments is easy to affect the esthetic effect of implant rehabilitation in the anterior tooth region, especially when the soft tissue is thin, the metallic color may show through the soft tissue [56–61].

2.3.2. Zirconia

Highly polished zirconia, as a widely selected material for the transmucosal area of abutments/restorations in clinical practice, has attracted extensive attention due to its good esthetic performance and biocompatibility. It has a color and transparency similar to natural teeth, which can meet the esthetic requirements of implant rehabilitation in the anterior tooth region. At the same time, it has a good soft tissue response, can induce soft tissue cells to form a tight attachment on its surface, and reduce the occurrence of peri-implantitis [62]. Studies have shown that compared with titanium abutments, zirconia abutments have significantly less bleeding on probing and milder inflammation of peri-implant soft tissues [63]. In addition, its smooth surface is not easy to adsorb plaque and pigment, with good cleaning performance, which is conducive to patients' oral hygiene maintenance. However, the mechanical properties of zirconia are relatively weak, and there is a risk of abutment fracture when subjected to large occlusal loads [64], which is the main limiting factor for its clinical application.

2.3.3. Clinical Selection Strategy of Titanium and Zirconia

Based on this, clinical material selection needs to comprehensively consider the implant site, soft tissue thickness and patients' occlusal conditions:

- For the anterior esthetic region or patients with soft tissue thickness ≤2 mm, zirconia or a combination of titanium base + zirconia abutment is preferred. For patients with high occlusal load, the thickness of zirconia abutment should be optimized to ≥1.5 mm, or a titanium base should be used to enhance mechanical properties;
- For the posterior tooth region with low esthetic requirements, titanium abutments are preferred. If patients have esthetic needs, a composite design of titanium base + zirconia outer layer can be adopted to avoid pure zirconia abutments bearing excessive occlusal force;
- In addition, for patients with poor oral hygiene maintenance, zirconia abutments with good cleaning performance can be preferred regardless of the implant site.

2.4. Peri-implant Soft Tissue Phenotype

2.4.1. Composition and Classification of Soft Tissue Phenotype

Peri-implant soft tissue phenotype is a core biological factor affecting the stability of the TBC, including three core indicators: mucosal thickness (MT), keratinized mucosa width (KMW) and supracrestal tissue height (STH) [65]. The clinical thresholds of each indicator and their effects on implant rehabilitation are as follows:

- Mucosal thickness: According to the mucosal thickness, it can be divided into thin gingival biotype (<2 mm) and thick gingival biotype (≥2 mm). The thin gingival biotype is characterized by thin gingival tissue, less connective tissue and rich blood vessels, with weak resistance to bacterial invasion and mechanical stress, which is prone to inflammatory reactions, leading to mucosal recession and marginal bone resorption, and also affecting the esthetic effect of the anterior tooth region [66,67]; the thick gingival biotype has thicker gingival tissue and rich connective tissue, with strong resistance to inflammation, and the peri-implant soft tissues are relatively stable.
- Keratinized mucosa width: When KMW ≥2 mm, the peri-implant tissues can better resist bacterial invasion and mechanical stimulation, reducing the risk of peri-implant mucositis and peri-implantitis; when KMW <2 mm, the tissue health status is poor, and the mucosa is prone to displacement and loosening during mastication, affecting the stress distribution of the implant and leading to marginal bone resorption [68–71]. In clinical practice, soft tissue grafting can be used to improve patients with insufficient keratinized mucosa width, among which free gingival graft (FGG) combined with apically positioned flap (APF) is the optimal surgical method for KMW augmentation around implants [72].
- Supracrestal tissue height (STH): Refers to the vertical height of soft tissue from the peri-implant mucosal margin to the alveolar crest, which can be measured circumferentially around the implant. It is composed of sulcular epithelium, junctional epithelium and supracrestal connective tissue, and the peri-implant STH is usually higher than that of natural teeth [73]. STH plays a key role in the pattern of marginal bone resorption; a short STH at the time of implantation is often accompanied by marginal bone resorption, which results from the physiological establishment of soft tissue components during the healing period and is not affected by implant design or restoration method [74–80]. A study took 3 mm as the critical value of STH [81]. Combined with the latest research evidence and anatomical differences between anterior and posterior teeth [82,83], STH can be clinically divided into short STH (<3 mm) and long STH (≥3 mm) [84]. A long STH is more conducive to the long-term stability of peri-implant tissues, but an excessively long STH is prone to the formation of a deep peri-implant pocket at the implant site, which is conducive to the colonization of periodontal pathogens, leading to difficult plaque control and persistent inflammation, thus affecting peri-implant health.

2.4.2. Improvement Methods of Soft Tissue Phenotype

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For patients with poor peri-implant soft tissue conditions, various soft tissue grafting techniques can be used to improve the phenotype in clinical practice. The core improvement goal is to achieve MT ≥2 mm, KMW ≥2 mm and STH ≥3 mm. The commonly used improvement methods are:

- To increase mucosal thickness or supracrestal tissue height, double membrane technique combined with connective tissue graft (CTG) or acellular dermal matrix (ADM) can be adopted, which can provide a good environment for soft tissue growth and promote soft tissue proliferation and thickening. Clinical studies have shown that the mucosal thickness can be increased by an average of 1-2 mm [85];
- To increase the width of keratinized mucosa, guided bone regeneration can be first used to provide bone support for free gingival graft, and then free gingival graft can be performed. Among them, the surgical method of APF combined with FGG has a significant effect, and the width of keratinized mucosa can be increased by an average of 3-4 mm [86].

2.5. Design and Management of Implant Superstructure

The healing mode after implant placement is divided into submerged healing and non-submerged healing. Non-submerged healing requires simultaneous placement of a healing abutment to achieve transmucosal healing. At this time, the sealing and maturation of peri-implant soft tissues start synchronously with the osseointegration process, and some scholars believe that the maturation and stability of soft tissues take 3 months. After the osseointegration and soft tissue integration are stable, the healing abutment needs to be replaced with a permanent abutment, and the morphology of the healing abutment and permanent abutment is closely related to the stability of soft tissues. The transmucosal height and angle of the healing abutment [87], and repeated abutment disassembly [88,89] may have an adverse effect on peri-implant bone remodeling. Therefore, ensuring the morphological consistency from the healing abutment to the permanent abutment is crucial to maintaining the stability of the soft tissue interface. The concept of one abutment one time is precisely proposed based on the core demand for soft tissue stability [90].

2.5.1. Abutment Height

The transmucosal height of the healing abutment/permanent abutment is an important factor affecting peri-implant marginal bone loss. A number of clinical studies and animal experiments have shown that the smaller the abutment height, the more obvious the MBL [91–95]. The reason is that when the abutment height is small, the restoration-abutment interface is closer to the alveolar crest, and bacteria at the microgap are more likely to invade the bone tissue and induce inflammatory reactions leading to bone resorption. For example, a study on implant bone loss (IBL) with two different abutment heights found that at 3 months after surgery, the IBL of the 1 mm abutment group (0.83 ± 0.19 mm) was significantly higher than that of the 3 mm abutment group (0.14 ± 0.08 mm); at 6 months after surgery, the IBL of the 1 mm abutment group was still significantly higher (0.91 ± 0.19 mm vs 0.11 ± 0.09 mm) [96]. However, the abutment height is not the higher the better. A study pointed out that when the abutment height exceeds 4 mm, although marginal bone resorption is reduced, the risk of mechanical complications of the restoration increases significantly [97].

At present, there is no unified conclusion on the optimal threshold of abutment height. The main reasons for the controversy are: the differences in neck design of different implant types (bone-level/tissue-level) lead to different adaptability of abutment height; there are individual differences in patients' bone and soft tissue conditions (such as alveolar crest height and STH value), and a single threshold cannot meet all clinical cases. The clinical response strategies are as follows: a abutment height of 2-4 mm is recommended for bone-level implants; tissue-level implants can relax the threshold to 1-5 mm due to the advantages of neck design; the combined application of abutment height and platform switching design has a synergistic effect [98]. Platform switching moves the microgap away from the alveolar crest, and an appropriately heighted abutment provides stable support for soft tissues. In clinical practice, an abutment height of about 3 mm is preferred for combined application [99], balancing bone tissue stability and restoration safety.

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2.5.2. Emergence Angle

The Emergence Angle is defined as the angle of the transitional contour of the implant restoration determined by the relationship between the abutment surface and the long axis of the implant. The Emergence Angle of the abutment/restoration is closely related to the occurrence of peri-implantitis. Studies have found that a large Emergence Angle (≥30 degrees) will significantly increase the risk of peri-implantitis. The reason is that this angle will change the stress distribution of peri-implant soft tissues, making the soft tissues bear excessive local tension, leading to damage to their integrity and providing opportunities for bacterial invasion; especially when the Emergence Profile is convex and splinted crown restoration is performed with adjacent implants in the mesial and distal, bone-level implants in the middle position are more prone to peri-implantitis. In tissue-level implants, the correlation between Emergence Angle and peri-implantitis is relatively weak, which is related to the special design of this type of implant that can better buffer stress [100–104]. Therefore, in clinical design, the Emergence Angle should be strictly controlled within 30 degrees, and this index needs to be more strictly controlled for bone-level implants.

2.5.3. Emergence Profile

The Emergence Profile is defined as the contour of a tooth or restoration (such as a crown on a natural tooth or implant abutment) related to adjacent tissues, which can be divided into straight, concave and convex. This design is a key factor affecting the health of peri-implant soft tissues. A convex contour will form a narrow space at the implant neck, which is not conducive to oral hygiene cleaning, easy to cause plaque accumulation and induce inflammation, and also easy to cause mucosal recession; a concave or gentle Emergence Profile is more conducive to soft tissue health. A concave contour can guide the natural formation of interdental papilla and form a good subgingival space for easy cleaning by patients; a gentle Emergence Profile can make the soft tissue stress uniform, reduce stress concentration and lower the incidence of inflammation. A clinical comparative study showed that implants with a concave Emergence Profile had significantly lower bleeding on probing index and plaque index of peri-implant soft tissues than those with a convex contour [102]. A 12-month randomized controlled trial (RCT) by Siegenthaler et al. also found that the incidence of mucosal recession in the convex group reached 64.3%, much higher than 14.3% in the concave group and 31.4% in the control group, confirming that implant provisional restorations with a concave Emergence Profile can achieve higher mucosal margin stability than convex ones within 12 months of loading [105].

At present, academic research on Emergence Profile has formed a variety of classification concepts, such as critical and sub-critical zone [106], esthetic biological contour (EBC) zone [107], deep zone、transition zone、cervical zone [108], etc. The core idea is to realize soft tissue shaping through the shaping of restorations in different areas, while balancing restorative and biological principles [109]. The dual-zone concept of Biological Room (BR) and Restorative Room (RR) proposed by Fabbri et al. in 2025 has important clinical guiding significance. This concept divides the implant subgingival complex into the apical biological functional zone and the coronal restorative functional zone, clarifies the anatomical location, size specification, morphological design, material selection and clinical operation principles of the two zones, provides a unified biologically oriented implant rehabilitation criterion for clinical dentists and technicians, can optimize the integration effect of hard and soft tissues, reduce the risk of peri-implant diseases, and improve the long-term success rate of implant rehabilitation [110].

In summary, the transmucosal design of the implant superstructure needs to be comprehensively considered in combination with implant type, patients' bone and soft tissue conditions and restoration needs, with the core of achieving a harmonious adaptation between soft tissues and restorations through standardized and personalized design.

4. Clinical Recommendations in Practice

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In clinical dental implant rehabilitation, to ensure the long-term stability of the TBC and improve the success rate of implant rehabilitation, a comprehensive consideration of multiple factors and formulation of personalized schemes are required. The core clinical recommendations are as follows:

- In the implant selection stage, implants with platform switching design and cervical micro-rough surface are preferred.

-Tapered internal connection (such as Morse taper connection) with good stability and sealing performance should be adopted for the abutment connection. Original abutments and screws, or third-party abutments authorized by original factory data should be used as much as possible to avoid microgaps and uneven stress caused by uncertified abutments.

-The transmucosal materials of abutments/restorations should be selected according to the implant site, soft tissue thickness and patients' occlusal conditions: zirconia materials are preferred for the anterior esthetic region or patients with soft tissue thickness ≤2 mm; for patients with high occlusal load, the thickness of zirconia abutment should be optimized (≥1.5 mm) or a titanium base composite design should be adopted; titanium materials can be used for the posterior tooth region, and a titanium base + zirconia outer layer design can be adopted for patients with esthetic needs.

-For patients with poor peri-implant soft tissue conditions, soft tissue grafting techniques should be used in a timely manner to improve the phenotype, such as increasing the width of keratinized mucosa by FGG combined with APF, and increasing mucosal thickness by double membrane technique combined with CTG or ADM, so as to ensure the clinical goals of KMW ≥2 mm, STH ≥3 mm and MT ≥2 mm around the implant.

- In the design of the implant superstructure, the principle of one abutment one time or minimizing the replacement of healing abutments should be strictly followed, and the morphological consistency between the healing abutment and the permanent abutment should be ensured; the transmucosal height of the abutment should be selected according to the implant type, 2-4 mm is recommended for bone-level implants, and 1-5 mm for tissue-level implants, with priority given to combined application with platform switching design; the Emergence Angle should be strictly controlled to <30 degrees; concave or gentle Emergence Profiles should be preferred to reduce the risk of plaque accumulation and mucosal recession caused by convex contours.

-Strengthen oral hygiene guidance for patients to improve their plaque control ability and reduce the risk of peri-implantitis; at the same time, according to the implant type, patients' bone conditions and restoration needs, control the design and management details of the transmucosal area throughout the process to achieve the synergistic stability of all components of the TBC.

5. Research Perspectives

Although certain achievements have been made in the research on the TBC at present, there are still many unknown fields to be explored. Future research can further investigate the biological mechanism of the TBC and clarify the interaction between various influencing factors, so as to provide a more solid theoretical basis for the optimization of clinical treatment schemes.

In addition, with the continuous development of materials science and biomedical engineering, the research and development of new implant, abutment and restoration materials to improve their biocompatibility, mechanical properties and esthetic effect will be an important direction for future research; at the same time, with the help of advanced technologies such as computer-aided design and manufacturing (CAD/CAM) and 3D printing, precise design and personalized manufacturing of implant rehabilitation can be realized to further improve the quality and long-term stability of implant rehabilitation.

For the controversial points in current research, such as the clinical adaptation standards of micro-thread design, the personalized threshold of abutment height, and the long-term mechanical properties of zirconia materials, multi-center, large-sample and long-term follow-up clinical studies need to be carried out to accumulate clinical data with unified standards; at the same time, evidence-based medicine methods can be combined to systematically integrate and analyze existing research to provide clear evidence-based medical evidence for controversial clinical issues.

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