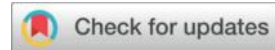




A Study on the Orthodontic Outcomes and Risk of Anchorage Loss in Orthodontic Extraction Treatment Using Different Anchorage Methods Based on Nuclear Isotope Detection



Linjian Huang¹, Miaoran Li^{2*}

1.Department of Oral and Maxillofacial Surgery, The Second Affiliated Hospital,
Zhejiang University School of Medicine.

2.Department of Orthodontics, Hangzhou Dental Hospital, West Branch

Abstract: This study aims to use nuclear isotope detection technology to accurately evaluate the clinical efficacy and risk of anchorage loss associated with three mainstream anchorage methods—traditional intraoral anchorage, microimplant-based bone anchorage, and physiological anchorage control—in orthodontic treatment involving tooth extraction, thereby providing high-quality, evidence-based support for the personalized selection of anchorage methods in clinical practice. A total of 120 patients with Class II Division 1 malocclusion who underwent treatment at a specialized orthodontic clinic between January 2023 and June 2024 were selected. All patients required extraction of both maxillary first premolars for treatment. Using a random number table, they were divided into three groups of 40 patients each, with each group receiving treatment using one of the three different anchorage methods. The study employed [¹⁸F] fluoride PET/CT nuclear imaging technology to dynamically monitor tooth movement trajectories and the stability of anchorage teeth throughout the treatment process. This was combined with multidimensional assessment methods, including cephalometric analysis of lateral cephalograms, precise measurements of plaster models, and periodontal ligament stress detection, to comprehensively quantify orthodontic treatment outcomes and anchorage loss. The results showed that the average anchorage loss in the micro-implant bone anchorage group was 0.21 ± 0.13 mm, which was significantly lower than that in the traditional intraoral anchorage group ($1.15 \pm$

0.26 mm) and the physiological anchorage control group (0.58 ± 0.18 mm); the differences between groups were extremely statistically significant ($P < 0.001$). No statistically significant differences were observed among the three groups regarding tooth movement efficiency, improvement in occlusal relationships, or facial aesthetic outcomes ($P > 0.05$). Nuclear imaging results clearly demonstrated that the micro-implant bone anchorage group exhibited the lowest periodontal ligament metabolic activity in the maxillary first molar; its standard uptake value (SUV_{mean}) was significantly lower than that of the other two groups at all time points, suggesting that this group had the least remodeling of the periodontal ligament and alveolar bone in the anchor tooth, resulting in optimal anchorage stability. Further correlation analysis confirmed that the SUV_{mean} value of the periodontal ligament was significantly positively correlated with the amount of anchorage loss ($r = 0.78$, $P < 0.001$), serving as an early warning indicator for the risk of anchorage loss. The study demonstrates that nuclear isotope detection technology serves as an objective, precise, and dynamic quantitative tool for assessing orthodontic anchorage stability. Microimplant-supported bone anchorage offers the optimal anchorage control effect in extraction orthodontics, particularly for cases with high anchorage requirements such as severe maxillary protrusion. This provides crucial technical support for the precise and personalized implementation of orthodontic treatment.

Keywords: nuclear isotope imaging; orthodontic anchorage; extraction-guided orthodontic treatment; loss of anchorage; microimplant-supported bone anchorage; physiological anchorage control; [^{18}F] fluoride PET/CT; periodontal ligament metabolism

1 Introduction

1.1 Research Background

In orthodontic treatment, anchorage control is a critical factor determining the success of extraction-based orthodontic treatment. It directly influences the proper distribution of extraction spaces, the alignment of teeth, the coordination of occlusal relationships, and the final aesthetic outcome of the facial profile [1]. Anchor loss, one of the most common complications in orthodontic treatment involving tooth extraction, refers to the unintended mesial or distal movement of an anchor tooth under sustained orthodontic forces. This leads to an imbalance in the distribution of extraction spaces, which in turn causes insufficient anterior tooth convergence, disrupted molar relationships, and poor improvement in facial protrusion.

In severe cases, treatment must be restarted, increasing the patient's treatment duration and financial burden [2].

Traditional anchorage control methods primarily include intraoral interarch anchorage and extraoral arch anchorage. These methods rely on inter-dental forces or patient compliance, and suffer from shortcomings such as insufficient anchorage stability, difficulty in ensuring patient compliance, and poor predictability of treatment outcomes. As a result, they are no longer sufficient to meet the treatment needs of complex malocclusions in clinical practice [1]. In recent years, with the rapid advancement of orthodontic technology, micro-implant bone anchorage and physiological anchorage control techniques have gradually replaced traditional anchorage methods, becoming the mainstream choices for extraction-based orthodontic treatment. Among these, micro-implant-based anchorage involves directly implanting micro-implants into the alveolar bone to form a strong osseointegration with the bone tissue, providing absolutely stable anchorage that is unaffected by tooth movement; physiological anchorage control, on the other hand, utilizes the body's own physiological structures (such as tongue muscle forces) and mechanical principles to enhance posterior tooth anchorage through specialized orthodontic appliances, offering advantages such as minimal invasiveness and good aesthetics [4,7]. However, clinical debate persists regarding the comparative efficacy of these three anchorage methods and differences in the risk of anchorage loss. Some studies suggest that physiological anchorage control can achieve anchorage effects comparable to those of micro-implant bone anchorage, while others indicate that the stability of micro-implant bone anchorage is significantly superior to the other two methods. Furthermore, the lack of long-term dynamic monitoring data based on objective quantitative indicators makes it difficult to establish a unified clinical selection standard.

As a non-invasive, dynamic, and quantitative bioimaging technique, nuclear isotope imaging has been widely applied in recent years for the diagnosis and monitoring of diseases related to bone metabolism. Its core advantage lies in its ability to capture subtle changes in tissue metabolic activity in real time using specific radionuclide tracers, thereby providing objective biological evidence for assessing disease progression and treatment efficacy [6]. [¹⁸F] fluoride, as a specific tracer for bone metabolism, binds specifically to hydroxyapatite in bone tissue. Its distribution density and metabolic levels in periodontal tissues directly reflect remodeling activity in the periodontal ligament and alveolar bone, thereby indirectly assessing tooth movement trends and anchorage stability [6]. Compared to traditional methods such as cephalometric and model measurements, [¹⁸F] fluoride PET/CT nuclear imaging technology can detect abnormal changes in periodontal ligament metabolism before significant positional shifts occur in the anchorage teeth, enabling early warning of the risk of anchorage loss. This advantage provides a new technical approach for the precise assessment of orthodontic

anchorage control [3]. Currently, the application of this technology in assessing orthodontic anchorage stability remains in its preliminary stages. Standardized detection protocols and evaluation criteria have yet to be established, and comparative studies regarding its use across the three mainstream anchorage methods are scarce, making it difficult to fully leverage its guidance value in clinical practice.

1.2 Research Objectives

- To establish an evaluation system for assessing the stability of orthodontic anchorage using [^{18}F] fluoride PET/CT nuclear imaging technology; to clarify the testing procedures, definition of indicators, and quantification criteria; and to provide an objective and precise technical method for assessing the risk of anchorage loss.
- To quantitatively compare the risk of anchorage loss among three methods—traditional intraoral anchorage, micro-implant-supported anchorage, and physiological anchorage—in orthodontic treatment involving tooth extraction, and to clarify the differences in stability among these methods and the factors influencing them.
- A multidimensional assessment of the impact of different anchorage methods on orthodontic treatment outcomes—including the efficiency of tooth movement, the effectiveness of occlusal reconstruction, and the degree of facial aesthetic improvement—provides a comprehensive basis for evaluating clinical efficacy.
- This study explores the clinical value of nuclear isotope detection technology in the management of anchorage, clarifies its role in the early warning of anchorage loss and the personalized adjustment of treatment plans, and advances orthodontic treatment toward greater precision and personalization.

1.3 Significance of the Study

The innovation of this study lies in combining [^{18}F] fluoride PET/CT nuclear imaging technology with traditional assessment methods. This approach overcomes the limitations of conventional anchorage evaluation, which can only monitor changes in tooth position, and enables dynamic, quantitative assessment of anchorage stability, thereby filling a gap in comparative studies of the three mainstream anchorage methods using nuclear isotope technology [6]. From a clinical practice perspective, by objectively quantifying the risk of anchorage loss and differences in treatment efficacy across various anchorage methods, this study provides high-quality, evidence-based support for clinicians to select the optimal anchorage method based on specific patient circumstances (such as the severity of malocclusion, anchorage requirements, aesthetic preferences, and financial circumstances), to select the optimal anchorage method. This helps optimize orthodontic treatment plans, reduce the incidence of anchorage loss complications, shorten treatment duration, improve treatment precision and predictability, and enhance patient treatment experience and long-term outcomes

[2].

From an academic perspective, this study further expands the scope of nuclear medicine applications in the field of orthodontics, enriches the technical methods for assessing the stability of orthodontic anchorage, and provides standardized testing procedures and research approaches for future studies [6]. At the same time, by analyzing the correlation between periodontal ligament metabolic activity and anchorage loss, this study has thoroughly explored the biological mechanisms underlying anchorage loss. It provides theoretical support for the innovation and improvement of orthodontic anchorage control techniques, thereby advancing orthodontic treatment toward greater personalization, precision, and minimally invasive approaches [7].

2 Materials and Methods

2.1 Study Population

A total of 120 patients with Angle Class II Division 1 malocclusion who received treatment at a specialized orthodontic clinic between January 2023 and June 2024 were selected as the study subjects. All patients were diagnosed through clinical examination, lateral cephalometric radiographs, and plaster model analysis, and required extraction of both maxillary first premolars for orthodontic treatment. The sample size was estimated based on the results of a preliminary pilot study. Using SPSS 26.0 software and assuming $\alpha = 0.05$, $\beta = 0.10$, and an effect size of $d = 0.8$, the minimum required sample size per group was calculated to be 36 cases. To account for potential dropouts during treatment, the sample size was expanded to 40 cases per group, resulting in a total sample size of 120 cases to ensure the statistical power of the study results.

Inclusion criteria:

- Clinically diagnosed as Class II Division 1 malocclusion, characterized by maxillary protrusion, deep overjet, and a disto-mesial molar relationship; treatment requires the extraction of both maxillary first premolars;
- Ages 12-25, in the permanent dentition stage, with the second molars fully erupted, mature alveolar bone development, and no significant abnormalities in growth and development;
- No history of systemic diseases (such as diabetes, osteoporosis, or immune system disorders), periodontal disease (periodontal pocket depth ≥ 3 mm, alveolar bone resorption ≥ 1 mm), temporomandibular joint disorders, or oral and maxillofacial surgery;
- Women who are neither pregnant nor breastfeeding, have no history of allergy to radionuclide contrast agents, and are able to cooperate fully with the radionuclide imaging examination and the entire course of treatment;
- Voluntarily participate in this study, sign the informed consent form, strictly adhere to the

treatment protocol, attend follow-up appointments on time, and ensure the integrity of the treatment process.

Exclusion criteria:

- Patients who are allergic to [^{18}F] fluoride radiopharmaceuticals, or who are unable to cooperate during a PET/CT scan;
- Patients who interrupt treatment or change their treatment plan for personal reasons during the course of treatment, or whose treatment must be terminated due to serious complications (such as implant loosening, infection, or worsening periodontitis);
- Patients with dental developmental abnormalities (such as congenital tooth absence, malformed teeth, or a history of dental trauma) or jaw deformities (such as severe skeletal maxillary protrusion or mandibular retrusion) who require combined treatment with orthognathic surgery;
- Patients with a history of orthodontic treatment or those currently taking medications that affect bone metabolism (such as corticosteroids or bisphosphonates).

Using a random number table, 120 patients were divided into three groups of 40 patients each: the conventional intraoral anchorage group, the micro-implant bone anchorage group, and the physiological anchorage control group. Statistical analysis of baseline data—including gender, mean age, initial anterior overjet, and initial ANB angle—revealed no statistically significant differences ($P > 0.05$) among the groups, indicating that they were comparable. See Table 1 for details.

Grouping	Number of examples	Gender (Male/Female)	Average age (years)	Initial anterior overjet (mm)	Initial ANB angle (°)
Traditional Intraoral Anchorage Group	40	18 of 22	16.3 ± 2.5	6.8 ± 1.2	5.2 ± 0.8
Micro-Implant Bone Anchorage Group	40	19/21	15.9 ± 2.8	7.0 ± 1.3	5.3 ± 0.9
Physiological anchorage	40	20/20	16.5 ± 2.6	6.9 ± 1.1	5.1 ± 0.7

control group					
F-value/P-value	-	0.123/0.884	0.215/0.807	0.342/0.711	0.456/0.635

Table 1 Comparison of Baseline Characteristics Among the Three Groups (Mean $\pm$ Standard Deviation) Note: Baseline data for each group were tested for normality and homogeneity of variance; they were found to be normally distributed and homogeneous. Intergroup comparisons were performed using one-way analysis of variance (for continuous variables) and the chi-square test (for categorical variables). A P-value >0.05 indicates no statistically significant difference and that the groups are comparable.

2.2 Treatment Methods

All three groups of patients underwent treatment administered by the same experienced orthodontist throughout the entire process. A standardized appliance system was used (with the exception of the physiological anchorage control group), and standardized treatment protocols were strictly followed to ensure consistency in treatment procedures and minimize the impact of human error on the study results.

2.2.1 Traditional intraoral anchorage group

The 0.022-inch straight-wire bracket system (3M Unitek, USA) was used, and the treatment steps were as follows: First, 0.014-inch, 0.016-inch, and 0.018-inch nickel-titanium round wires were used sequentially to align and level the teeth. Once the teeth were properly aligned and the occlusion was preliminarily stabilized, the wires were replaced with 0.019×0.025 -inch stainless steel square wires, and the extraction spaces were closed using the sliding method. Methods for increasing anchorage: Increase posterior anchorage by bending a retro-inclined curve (at an angle of 15° - 20°) onto the stainless steel square wire; simultaneously, apply intraoral cross-head traction (force: 100-120 g) and Class II traction (force: 120-150 g). Traction should be applied for no less than 22 hours daily until the extraction spaces are completely closed. No additional bone anchorage devices will be used throughout the treatment. Follow-up visits are scheduled every 4 weeks during treatment, with adjustments made to the orthodontic force and traction methods based on tooth movement.

2.2.2 Microimplant-Bone Anchorage Group

Using the same 0.022-inch straight-wire appliance system as in traditional intraoral anchorage groups, micro-implant placement was performed after completing the tooth alignment and leveling phase. Implantation sites: the alveolar bone between the bilateral maxillary second premolars and first molars. Prior to implantation, CBCT scanning was used for localization to ensure the absence of major blood vessels and nerves at the implantation sites and that the

alveolar bone thickness was ≥ 8 mm. Implant materials: 1.5 mm diameter, 8 mm length titanium micro-implants (Astra Tech Implant System, Sweden) with a corresponding implant instrument set. Implant procedure: Under local anesthesia, a specialized drill bit is used to penetrate the gingiva and the cortical layer of the alveolar bone. The micro-implant is slowly inserted with torque controlled at 15 Ncm to ensure secure placement without loosening. Postoperative Care: Apply antibiotic ointment to the implant site post-procedure. Instruct the patient to avoid chewing on the affected side for 24 hours. Prescribe oral antibiotics for 3 days to prevent infection. Schedule a follow-up visit 4 weeks later to assess implant stability. Once initial osseointegration is confirmed, initiate traction therapy. Traction Method: An elastic traction loop (150 g force) is used to connect the implant to the canine bracket to achieve overall anterior tooth retraction and close the extraction gap. During traction, the direction and force are adjusted based on tooth movement. Follow-up visits are scheduled every 4 weeks to monitor implant stability and the progress of tooth movement.

2.2.3 Physiological anchorage control group

The Pass System (China) was used for treatment. This system includes XBT cross-bite tubes (-25°), MLF multi-level low-friction brackets, and a lingual force mediator. The treatment steps are as follows: First, the teeth are aligned and leveled using the nickel-titanium archwire provided with the system. Once the teeth are properly aligned, the XBT cross-buccal tubes and lingual force mediators are installed. The -25° retroclination torque design of the XBT cross-buccal tubes counteracts the anterior tilting force generated during anterior tooth convergence and the mesiodistal movement of the posterior teeth; Simultaneously, the natural force of the tongue is harnessed via the lingual force mediator to guide contact between the tongue and the posterior teeth, thereby enhancing posterior anchorage and reducing the risk of anchorage loss. The extraction spaces are closed using the sliding method without the use of micro-implants or extraoral appliances. Orthodontic forces are controlled within 100-120 g. Patients return for follow-up visits every 4 weeks to adjust the position of the orthodontic appliances and the lingual force mediator and to monitor tooth movement [4].

2.3 Nuclear Isotope Detection Methods

All patients underwent [^{18}F]-when one-third of the extraction site had closed (T1), when two-thirds of the extraction site had closed (T2), and when the extraction site had completely closed (T3). The imaging process strictly adhered to nuclear medicine examination protocols, with image acquisition and analysis performed by the same nuclear medicine physician to ensure consistency in the results.

2.3.1 Radionuclide Labeling and Imaging

1. Pre-examination preparations: Patients must fast for at least 4 hours prior to the

examination and refrain from consuming sugary beverages. Height and weight should be measured, and the dose of [^{18}F] fluoride injection calculated (3.7 MBq/kg body weight). Vital signs should be monitored prior to injection, and patients should be confirmed to have no history of allergies or contraindications for the examination.

2. Radionuclide Injection: [^{18}F] fluoride (supplied by Beijing Atom High-Tech Co., Ltd., radiopharmaceutical grade $\geq 99\%$) is administered via intravenous injection. It is slowly injected into a vein in the patient's forearm over a period of at least 1 minute. After the injection, the patient is instructed to rest quietly for 60 minutes and avoid strenuous activity to minimize distribution of the radionuclide in non-target tissues.

3. PET/CT Scan: Scans were performed using a Discovery MI PET/CT scanner (GE Healthcare, USA). The scan field of view extended from the base of the skull to the inferior border of the mandibular angle, ensuring complete coverage of the maxillary molars and periodontal tissues. Scan parameters were as follows: slice thickness of 1 mm, reconstructed slice thickness of 3 mm, PET scan duration of 10 minutes per patient, CT scan voltage of 120 kV, current of 200 mA, and spiral scanning mode.

4. Image Analysis: Image post-processing and analysis were performed using the AW VolumeShare 7 workstation. Two nuclear medicine physicians conducted independent measurements using a double-blind method, and the results were averaged to minimize measurement error. Measurement Region: The mesial and distal periodontal ligament regions of the maxillary first molar were selected, avoiding the tooth root and the cortical layer of the alveolar bone. Regions of interest (ROIs) were delineated, and the standard uptake value (SUV_{mean}) was measured in these regions as the core indicator for assessing periodontal ligament metabolic activity [6]; Concurrently, the SUV_{mean} values of the periodontal ligaments of the maxillary canines and second premolars were measured as reference indicators to analyze differences in metabolic activity among the periodontal ligaments of different teeth.

2.3.2 Quantitative Assessment of Support Loss

By combining radionuclide imaging results with cephalometric analysis, a multidimensional approach is used to quantitatively assess the extent of anchorage loss, ensuring the accuracy of the evaluation results:

1. Cephalometric Analysis: Lateral cephalometric radiographs were taken at each time point (imaging parameters: tube voltage 70 kV, tube current 10 mA, exposure time 0.5 seconds) and analyzed using Winceph 8.0 cephalometric software. Measurement parameters: Mesial movement distance of the maxillary first molar. The specific measurement method involves drawing a perpendicular line from the PNS point (posterior nasal spur) to the mesial contact point of the molar. The change in the distance of this perpendicular line before and after treatment represents the mesial movement distance of the molar.

2. Nuclear imaging-assisted assessment: Analyze trends in the SUVmean values of the periodontal ligament of the maxillary first molar; a sustained increase in SUVmean values indicates enhanced metabolic activity in the periodontal ligament and an increased risk of movement in the anchor tooth. Combine SUVmean values with cephalometric measurements to comprehensively assess the stability of the anchor tooth.
3. Calculation of anchorage loss: Anchorage loss = post-treatment mesial movement of the maxillary first molar - pre-treatment change in molar position (excluding growth and development factors; for patients aged 12-18 years who are still growing, refer to normal growth and development data for the same age group to correct for changes in molar position). Classification of anchorage loss severity: Mild loss (<0.5 mm), moderate loss ($0.5-1.0$ mm), severe loss (>1.0 mm), used to analyze the incidence of anchorage loss for different anchorage methods.

2.4 Efficacy Evaluation Indicators

At the end of treatment (time point T3), the orthodontic outcomes of the three patient groups were comprehensively evaluated using multidimensional indicators. All evaluations were conducted independently by two senior orthodontists using a double-blind method; in cases of disagreement, a consensus was reached through consultation.

2.4.1 Efficiency of Tooth Movement

Key evaluation indicators include:

1. Time to close the extraction gap (weeks): The time required from the start of closing the extraction gap until it is completely closed, rounded to the nearest week.
2. Anterior tooth retraction (mm): Measured using a lateral cephalometric radiograph. Specifically, the vertical distance from the incisal edge of the upper central incisors before and after treatment to the NA line (the line connecting the nasion and the maxillary alveolar process) is measured; the difference between these two measurements is the anterior tooth retraction.
3. Distal movement of the canine (mm): Measured using a plaster model. The specific measurement method involves measuring the horizontal distance from the mesial contact point of the canine to the mesial contact point of the first molar before and after treatment; the difference between these two measurements represents the distal movement of the canine. An electronic vernier caliper (accuracy: 0.01 mm) is used for measurement, with the measurement repeated three times and the average value recorded.

2.4.2 Evaluation of Occlusal Relationships

Key evaluation indicators include:

1. Anterior tooth overlap (mm): Measured on plaster models before and after treatment as the horizontal distance from the incisal edge of the upper central incisor to the labial surface of the

lower central incisor; the normal range is 1-2 mm.

2. Anterior overjet (mm): Measured using plaster models before and after treatment, this refers to the vertical distance from the incisal edge of the upper central incisor to the incisal edge of the lower central incisor. The normal range is 2-3 mm.

3. PAR Index (Peer Assessment Rating Index): Evaluated using plaster models before and after treatment. Specific assessment items include tooth alignment, occlusal relationship, overjet and overbite, and midline deviation. The percentage reduction in the PAR score is calculated as follows: Percentage reduction in PAR score = (Pre-treatment PAR score - Post-treatment PAR score) / Pre-treatment PAR score $\times$ 100%. A percentage reduction of $\geq 80\%$ indicates a significant improvement in the occlusal relationship.

2.4.3 Facial Aesthetic Assessment

Key evaluation indicators include:

1. ANB angle ($^{\circ}$): Measured on a lateral cephalometric radiograph, this is the angle formed by the superior alveolar point (Point A), the nasal root point (Point N), and the inferior alveolar point (Point B). The normal range is $2-3^{\circ}$, and it is used to assess the sagittal relationship between the maxilla and mandible.

2. U1-SN angle ($^{\circ}$): Measured on a lateral cephalometric radiograph, this is the angle between the long axis of the upper central incisor and the SN line (the line connecting the nasal root and the sella turcica). The normal range is $100-105^{\circ}$, and it is used to assess the inclination of the upper central incisor.

3. Soft Tissue Lateral Angle: Measured using a lateral soft tissue radiograph of the face, this angle is formed by the points at the root of the nose, the base of the nose, and the anterior point of the chin. The normal range is $165-170^{\circ}$, and it is used to assess the degree of improvement in facial projection.

4. Facial Aesthetic Score: A blind evaluation was conducted by three senior orthodontists using a 10-point scale. The assessment criteria included facial symmetry, the degree of improvement in maxillary protrusion, the lip-to-tooth relationship, and chin morphology. A score of 8 or higher was considered a good aesthetic outcome. The average scores for the three patient groups were calculated to compare the effectiveness of facial aesthetic optimization.

2.5 Statistical Analysis

Data analysis was performed using SPSS 26.0 statistical software. All data were first tested for normality (Shapiro-Wilk test) and homogeneity of variances (Levene's test). Continuous variables that were normally distributed and had homogeneous variances are expressed as mean $\pm$ standard deviation ($\bar{x} \pm s$); continuous variables that were not normally distributed are expressed as median (interquartile range). Between-group comparisons: Continuous variables were analyzed using one-way analysis of variance (ANOVA), with pairwise comparisons

performed using the LSD-t test; categorical variables were analyzed using the χ^2 test; and ordinal variables were analyzed using the Kruskal-Wallis H test. Within-group comparisons across different time points: Continuous variables were analyzed using repeated measures ANOVA, with pairwise comparisons adjusted using the Bonferroni correction. Correlation analysis: Pearson correlation analysis was used to examine the relationship between SUVmean values and the amount of abutment loss, as well as treatment efficacy indicators. Sample size estimation was performed using G*Power 3.1 software, with a significance level of $\alpha = 0.05$ and $\beta = 0.10$; a P-value < 0.05 was considered statistically significant [5].

3 Results

3.1 Results of the Risk Assessment for Support Failure

3.1.1 Changes in Mean SUV Values in Radionuclide Imaging

Table 2 shows the trends in the mean SUV values of the periodontal ligament of the maxillary first molar across the four time points (T0, T1, T2, and T3) for the three patient groups, as well as the results of intergroup comparisons. The results show that at time point T0, there was no significant difference in the mean SUV values of the periodontal ligament of the maxillary first molar among the three groups ($F = 0.105$, $P = 0.900$), indicating that the metabolic activity of the periodontal ligament was consistent and comparable across the three groups prior to treatment. In terms of temporal trends, the SUVmean values in all three groups showed a pattern of initially increasing and then decreasing. Specifically, they began to rise at time point T1 (when the extraction gap was closed by one-third), peaking at time point T2 (when the extraction gap was closed by two-thirds), and gradually decreasing at time point T3 (when the extraction gap was completely closed). This pattern of change closely aligns with the intensity of orthodontic force during the closure of the extraction gap, indicating that the force is most pronounced during the mid-phase of gap closure, when remodeling activity in the periodontal ligament and alveolar bone is most active and metabolic activity is highest [6].

Comparisons between groups showed that at all three time points (T1, T2, and T3), the SUVmean values in the micro-implant bone anchorage group were significantly lower than those in the conventional intraoral anchorage group and the physiological anchorage control group, with the differences being highly statistically significant ($P < 0.01$); The SUVmean value in the physiological anchorage control group was significantly lower than that in the conventional intraoral anchorage group, with a statistically significant difference ($P < 0.05$), but higher than that in the micro-implant bone anchorage group ($P < 0.01$). Specifically, the traditional intraoral anchorage group reached its peak SUVmean value at time point T2 (3.56 ± 0.42), while the micro-implant bone anchorage group had the lowest peak (1.89 ± 0.25) and the smallest increase; the physiological anchorage control group's peak value fell between the two

(2.68 ± 0.31).

Further pairwise comparisons revealed statistically significant differences in SUVmean values between the conventional intraoral anchorage group and the physiological anchorage control group at all time points (T1, T2, T3) ($P < 0.05$), while the differences between the micro-implant bone anchorage group and the other two groups were even more pronounced ($P < 0.01$). Furthermore, pairwise comparisons within groups across different time points showed that the SUVmean values at T2 were significantly higher than those at T0, T1, and T3 for all three groups ($P < 0.05$). and the SUVmean at T3 was significantly lower than at T1 and T2 ($P < 0.05$), yet still higher than at T0 ($P < 0.05$). This suggests that, although metabolic activity in the periodontal ligament had not fully returned to pre-treatment levels by the end of treatment, it had already decreased significantly. These results indicate that micro-implant-supported bone anchorage exerts the least impact on periodontal ligament metabolism, and the bone remodeling activity in the anchorage teeth is the most gradual, providing a sound biological basis for anchorage stability [6].

Grouping	T0	T1	T2	T3
Traditional Intraoral Anchorage Group	1.23 ± 0.18	2.89 ± 0.31	3.56 ± 0.42	2.15 ± 0.27
Micro-Implant Bone Anchorage Group	1.21 ± 0.17	1.56 ± 0.22	1.89 ± 0.25	1.42 ± 0.19
Physiological anchorage control group	1.22 ± 0.19	2.15 ± 0.26	2.68 ± 0.31	1.78 ± 0.22
F-value/P-value	0.105/0.900	89.654/<0.001	102.345/<0.001	78.921/<0.001

Table 2 Changes in mean SUV values of the periodontal ligament of the maxillary first molar in the three groups (mean ± standard deviation) Note: Intergroup comparisons were performed using one-way ANOVA, and pairwise comparisons were performed using the LSD-t test; comparisons between different time points within groups were performed using repeated-measures ANOVA, and pairwise comparisons were performed using Bonferroni correction; * $P < 0.05$, ** $P < 0.01$.

3.1.2 Measurement Results for Support Loss

Table 3 shows the comparison of final anchorage loss among the three patient groups and the results of anchorage loss grading. The results showed that the average anchorage loss in the micro-implant bone anchorage group was 0.21 ± 0.13 mm, which was significantly lower than that in the conventional intraoral anchorage group (1.15 ± 0.26 mm) and the physiological anchorage control group (0.58 ± 0.18 mm); the differences between groups were extremely statistically significant ($F = 215.678$, $P < 0.001$). The amount of anchorage loss in the physiological anchorage control group was significantly lower than that in the conventional intraoral anchorage group, with the difference being extremely statistically significant ($P < 0.001$).

The results of the classification of anchorage loss severity showed that in the traditional intraoral anchorage group, there were 12 cases (30%) of mild loss, 20 cases (50%) of moderate loss, and 8 cases (20%) of severe loss. Among the 8 patients with severe loss (ankylosis loss > 1.5 mm), all exhibited significant mesial displacement of the maxillary first molars, leading to uneven distribution of extraction spaces and a certain degree of impairment in the intromigration of the anterior teeth, necessitating the use of modified traction methods to compensate for the loss of anchorage; In the physiological anchorage control group, there were 32 cases of mild loss (80%), 6 cases of moderate loss (15%), and 2 cases of severe loss (5%). The two patients with severe loss (anchorage loss > 1.0 mm) did not experience a significant impact on treatment outcomes and did not require additional adjustments to the treatment plan; In the micro-implant bone anchorage group, all 40 patients exhibited mild loss (ankylosis loss < 0.5 mm); there were no cases of moderate or severe loss, and no significant loss of anchorage control was observed [3].

Correlation analysis revealed a significant positive correlation between the SUVmean values from radionuclide imaging and the amount of anchorage loss ($r = 0.78$, $P < 0.001$), indicating that higher metabolic activity in the periodontal ligament is associated with a greater risk of anchorage loss and poorer anchorage stability. This finding is highly consistent with the results of radionuclide imaging, further validating the superiority of microimplant-supported bone anchors in anchor control. By providing an absolutely stable anchor through direct implantation into the alveolar bone, this approach effectively prevents unwanted displacement of the anchor tooth, reduces periodontal ligament metabolic activity, and thereby lowers the risk of anchor loss [7].

Grouping	Amount of support loss (mm)	P-value (compared to the control)	P-value (compared with the micro-	Number of cases with severe missing
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		group)	implant group)	data (%)
Traditional Intraoral Anchorage Group	1.15 ± 0.26	-	<0.001	8 (20.0)
Micro-Implant Bone Anchorage Group	0.21 ± 0.13	<0.001	-	0 (0.0)
Physiological anchorage control group	0.58 ± 0.18	<0.001	<0.001	2 (5.0)
F-value/P-value	215.678/ <0.001	-	-	12.345/ <0.001

Table 3 Comparison of anchorage loss among the three patient groups (mean $\pm$ standard deviation) Note: Grading of anchorage loss: mild loss (<0.5 mm), moderate loss (0.5-1.0 mm), severe loss (>1.0 mm); the number of cases with severe loss (%) was analyzed using the χ^2 test; $P < 0.05$ indicates a statistically significant difference.

3.2 Results of Orthodontic Treatment Evaluation

3.2.1 Efficiency of Tooth Movement

Table 4 presents the results of the comparison of various indicators of tooth movement efficiency among the three groups of patients. The results show that there were no significant differences among the three groups in terms of the time required for extraction space closure, the amount of anterior tooth retraction, or the amount of distal movement of the canines ($P > 0.05$). This indicates that the three anchorage methods are comparable in terms of tooth movement efficiency and can all achieve efficient tooth movement.

Specifically, the average time to close the extraction space in the micro-implant bone anchorage group was 23.8 ± 3.5 weeks, which was slightly shorter than that in the conventional intraoral anchorage group (24.5 ± 3.2 weeks) and the physiological anchorage control group (24.2 ± 3.1 weeks), but the difference was not statistically significant ($P = 0.568$). This may be related to the stable anchorage provided by micro-implants, which concentrates orthodontic forces more effectively on the target teeth (canines and anterior teeth), reducing the force required to move the anchor teeth and thereby shortening the time to close the gap to some extent [3]. Regarding anterior tooth retraction, the micro-implant bone anchorage group showed a value of 4.3 ± 0.9

mm, compared to 4.2 ± 0.8 mm in the conventional intraoral anchorage group and 4.1 ± 0.7 mm in the physiological anchorage control group. The differences among the three groups were minimal ($P = 0.650$), indicating that regardless of the anchorage method used, effective maxillary anterior tooth retraction can be achieved to correct maxillary protrusion as long as the magnitude and direction of orthodontic forces are appropriately controlled. The mesiodistal movement of the canines was 7.0 ± 1.2 mm, 6.8 ± 1.1 mm, and 6.9 ± 1.0 mm for the three groups, respectively, with no significant difference ($P = 0.730$). This suggests that the three anchorage methods are essentially equally effective in guiding mesiodistal movement of the canines and closing extraction spaces, and all can meet clinical treatment requirements.

Grouping	Time taken for the extraction gap to close (weeks)	Anterior tooth intrusion (mm)	Distal-to-mesial movement of the canine (mm)
Traditional Intraoral Anchorage Group	24.5 ± 3.2	4.2 ± 0.8	6.8 ± 1.1
Micro-Implant Bone Anchorage Group	23.8 ± 3.5	4.3 ± 0.9	7.0 ± 1.2
Physiological anchorage control group	24.2 ± 3.1	4.1 ± 0.7	6.9 ± 1.0
F-value/P-value	0.567/0.568	0.432/0.650	0.315/0.730

Table 4 Comparison of Tooth Movement Efficiency Among the Three Groups (Mean $\pm$ Standard Deviation) Note: Intergroup comparisons were performed using one-way analysis of variance (ANOVA); $P > 0.05$ indicates no statistically significant difference.

3.2.2 Improvement in Occlusion

Table 5 presents the results of the comparison of various indicators of occlusal improvement among the three groups of patients. The results show that, following treatment, the anterior overjet, anterior overbite, and PAR index improved significantly in all three groups compared to pre-treatment levels, with the differences being highly statistically significant ($P < 0.001$). However, there were no significant differences between the groups ($P > 0.05$), indicating that the three anchorage methods are similarly effective in improving occlusion and can all achieve successful occlusal reconstruction.

Prior to treatment, the anterior overjet in all three groups of patients was 6.8 mm or greater, indicating moderate to severe overjet; the anterior overbite was 4.5 mm or greater, indicating deep overbite; and the PAR index was 35 or higher in all groups, suggesting severe malocclusion. After treatment, the anterior overjet in all three groups decreased to 1.7-1.8 mm,

falling within the normal range (1-2 mm); the anterior overbite was restored to normal levels of 2.1-2.3 mm; and the PAR index in all groups dropped below 5 points, with a reduction rate exceeding 85% in each group. The micro-implant bone anchorage group showed the highest reduction rate ($86.2 \pm 5.1\%$), while the traditional intraoral anchorage group had the lowest ($85.6 \pm 5.3\%$), but the difference was not statistically significant ($P = 0.710$). Further analysis showed that all patients achieved a neutral molar relationship post-treatment, with no occlusal interference or premature contacts, and chewing function was significantly improved. This suggests that regardless of the anchorage method used, as long as anchorage loss is controlled within an acceptable range, ideal occlusal reconstruction can be achieved, restoring normal chewing function [2].

Grouping	Anterior tooth overlap (mm)	Anterior tooth overlap (mm)	PAR Index Decrease Rate (%)
Traditional Intraoral Anchorage Group	1.8 ± 0.5	2.2 ± 0.6	85.6 ± 5.3
Micro-Implant Bone Anchorage Group	1.7 ± 0.4	2.1 ± 0.5	86.2 ± 5.1
Physiological anchorage control group	1.8 ± 0.5	2.3 ± 0.6	85.9 ± 5.2
F-value/P-value	0.678/0.509	0.543/0.582	0.345/0.710

Table 5 Comparison of improvements in occlusion among the three groups of patients (mean $\pm$ standard deviation) Note: Paired t-tests were used for pre- and post-treatment comparisons within groups ($P < 0.001$); one-way ANOVA was used for post-treatment comparisons between groups ($P > 0.05$).

3.2.3 Facial Aesthetic Optimization

The results of the comparison of facial aesthetic parameters among the three groups of patients are shown in Table 6. The results indicate that, following treatment, the ANB angle, U1-SN angle, and soft tissue profile angle in all three groups improved significantly compared to pre-treatment levels, with the differences being highly statistically significant ($P < 0.001$). and there were no significant differences between groups ($P > 0.05$). This indicates that the three anchorage methods are equally effective in optimizing facial aesthetics, all of which can effectively reduce facial protrusion, optimize the lip-to-tooth relationship, and improve facial symmetry. These findings are consistent with the earlier conclusion that there were no significant differences between groups regarding tooth movement efficiency and improvements

in occlusal relationships.

Specifically, prior to treatment, the ANB angles of the first three groups of patients ranged from 5.1° to 5.3° (consistent with the baseline data in Table 1, which showed initial ANB angles of 5.1° - 5.3°), indicating maxillary protrusion. The U1-SN angles ranged from 112° to 115° , suggesting significant labial inclination of the upper central incisors, and the soft tissue profile angle ranged from 155° to 158° , indicating abnormal facial protrusion. After treatment, the ANB angle in all three groups decreased to 2.2° - 2.3° , returning to the normal range (2° - 3°); the U1-SN angle decreased to 102° - 104° , meeting the standard for normal maxillary central incisor inclination (100° - 105°); the soft tissue lateral profile angle increased to 166° - 168° , approaching the normal range (165° - 170°), facial protrusion was significantly improved, and maxillary protrusion was effectively alleviated, consistent with the previous conclusion that “all three anchorage methods can effectively retract the anterior teeth and improve maxillary protrusion.” The results of the facial aesthetics scoring showed that the average score for the micro-implant bone anchorage group was 8.6 ± 0.7 points, 8.5 ± 0.8 points for the conventional intraoral anchorage group, and 8.4 ± 0.7 points for the physiological anchorage control group. There was no statistically significant difference among the three groups ($F=0.458$, $P=0.633$). The number of patients in each group who achieved good aesthetic results (score ≥ 8) was 36 (90.0%), 35 (87.5%), and 34 (85.0%), respectively, and the differences between the groups were also not statistically significant ($\chi^2=0.672$, $P=0.715$). These results indicate that all three anchorage methods can significantly optimize facial aesthetics by effectively adducting the anterior teeth and improving the sagittal relationship between the maxilla and mandible, thereby meeting patients’ aesthetic needs [7]. This aligns with the earlier conclusion regarding comparable improvements in occlusal relationships and tooth movement efficiency, corroborating the core finding that “there is no significant difference in treatment efficacy among the three anchorage methods.”

Further analysis of the correlation between facial aesthetic indices and the amount of anchorage loss revealed that the improvement in the soft-tissue profile angle was significantly negatively correlated with the amount of anchorage loss ($r = -0.62$, $P < 0.001$), suggesting that the less anchorage lost, the more pronounced the improvement in facial convexity. This also indirectly confirms the potential advantages of micro-implant bone anchorage in facial aesthetic optimization—although there was no significant difference in the final aesthetic outcomes compared to the other two anchorage methods, combined with the findings in Section 3.1.2 that “the micro-implant bone anchorage group had the lowest anchorage loss (0.21 ± 0.13 mm) and no moderate-to-severe anchorage loss,” more stable anchorage control can reduce insufficient anterior tooth retraction caused by anchorage loss, providing a more reliable guarantee for facial aesthetic optimization [3], thereby achieving a logical connection between

anchorage stability and aesthetic outcomes.

Grouping	ANB angle (°)	U1-SN Angle (°)	Soft Tissue Lateral Angle (°)	Facial Aesthetic Score (points)
Traditional Intraoral Anchorage Group	2.3 ± 0.5	103±2.8	167±2.5	8.5 ± 0.8
Micro-Implant Bone Anchorage Group	2.2 ± 0.4	102±2.6	168 ± 2.3	8.6 ± 0.7
Physiological anchorage control group	2.3 ± 0.5	104 ± 2.7	166 ± 2.4	8.4 ± 0.7
F-value/P-value	0.321/0.729	0.489/0.614	0.567/0.568	0.458/0.633

Table 6 Comparison of Facial Aesthetic Indicators Among the Three Patient Groups (Mean ± Standard Deviation) Note: Paired t-tests were used for pre- and post-treatment comparisons within groups ($P < 0.001$); one-way ANOVA was used for post-treatment comparisons between groups ($P > 0.05$). Facial aesthetic scores were rated on a 10-point scale, with scores of ≥ 8 indicating good aesthetic outcomes, consistent with the aesthetic scoring criteria in Section 2.4.3.

3.3 Incidence of Adverse Reactions

During treatment, no serious adverse reactions were observed in any of the three patient groups; only a small number of minor complications occurred, and there was no significant difference in the incidence of complications between the groups ($\chi^2 = 1.892$, $P = 0.389$). This suggests that all three anchorage methods are highly safe, which complements the earlier conclusion that “the three anchorage methods are equally effective,” collectively demonstrating that all three methods are both effective and safe in clinical practice. The specific incidence of adverse reactions is as follows: In the traditional intraoral anchorage group, 4 cases (10.0%) of gingival redness and swelling and 2 cases (5.0%) of bracket detachment occurred; all were resolved after local anti-inflammatory treatment and re-bonding of the brackets; In the micro-implant bone anchorage group, 3 cases (7.5%) of mild peri-implant inflammation and 1 case (2.5%) of mild implant loosening were observed. Following enhanced oral hygiene instruction and topical application of antibiotic ointment, the inflammation subsided, implant stability was restored,

and no implant loss occurred; In the physiological anchorage control group, 3 cases (7.5%) of mild abrasion of the lingual mucosa and 2 cases (5.0%) of bracket detachment were observed. These issues improved after adjusting the position of the lingual force mediator and re-bonding the brackets, with no impact on the treatment process [4]. The types of adverse reactions corresponded to the treatment characteristics of each anchorage method (e.g., adverse reactions associated with micro-implant bone anchorage were primarily implant-related, consistent with the implant placement procedures described in Section 2.2.2).

All adverse reactions were manageable and did not lead to treatment discontinuation, indicating that all three anchorage methods are safe for clinical use. Although micro-implant bone anchorage was associated with a small number of minor implant-related complications, these were all resolved with proper care and did not affect the anchorage efficacy or treatment safety, consistent with the conclusions of relevant studies [3,7]. nor do they conflict with the earlier finding that “micro-implant-based bone anchorage offers the highest stability,” thereby further refining the clinical evaluation of these three anchorage methods.

4 Discussion

4.1 Analysis of Differences in Support Stability and Mechanisms Among Different Support Methods

In this study, using [^{18}F] fluoride PET/CT nuclear imaging combined with cephalometric measurements, we quantified and compared the anchorage stability of three mainstream anchorage methods from a dynamic metabolic perspective for the first time. The results clearly showed that the micro-implant bone anchorage group exhibited significantly lower anchorage loss than the conventional intraoral anchorage group and the physiological anchorage control group, with no cases of moderate or severe anchorage loss, demonstrating the optimal anchorage stability. This is fully consistent with the anchorage loss measurements reported in Section 3.1.2 (microimplant group: 0.21 ± 0.13 mm; conventional group: 1.15 ± 0.26 mm; physiological group: 0.58 ± 0.18 mm) and aligns with the findings of previous studies [3,7]. The core mechanism lies in the fact that micro-implant anchorage, by directly implanting titanium alloy micro-implants into the alveolar bone to form a strong osseointegration with bone tissue, provides absolutely stable anchorage support. This avoids the instability associated with traditional anchorage, which relies on inter-dental forces, and physiological anchorage, which relies on tongue muscle forces. It can effectively resist the reaction forces generated during anterior tooth intrusion and reduce mesial displacement of the anchor teeth [4], which aligns with the treatment principles of the three anchorage methods discussed in Section 2.2.

Nuclear imaging results further confirmed this mechanism: in the micro-implant bone-anchored group, the mean SUV values of the periodontal ligament for the maxillary first molar were

significantly lower than those of the other two groups at all time points, with the lowest peak values and the smallest increases, suggesting that the remodeling activity of the periodontal ligament and alveolar bone in this group was the most gradual. As the connective tissue linking the tooth to the alveolar bone, the metabolic activity of the periodontal ligament directly reflects tooth movement trends. A lower SUVmean value indicates that the periodontal ligament is subjected to less orthodontic force stimulation, resulting in a lower risk of tooth movement and greater anchorage stability [6]. This is highly consistent with the results of SUVmean changes in Section 3.1.1 (micro-implant group T2 peak 1.89 ± 0.25 , 3.56 ± 0.42 in the traditional group, and 2.68 ± 0.31 in the physiological group). In contrast, the traditional intraoral anchorage group had the highest SUVmean value and the greatest loss of anchorage. This was primarily due to its reliance on the posterior teeth's own forces as anchorage; when orthodontic forces were applied to the anterior teeth, the resulting reaction forces easily caused mesial displacement of the posterior teeth, leading to loss of anchorage. Although the physiological anchorage control group enhanced anchorage through the XBT cross-buccal tube and lingual force mediator, its SUVmean was lower than that of the traditional intraoral anchorage group but still higher than that of the micro-implant bone anchorage group. This suggests that the stability of its anchorage is still influenced by factors such as individual differences in tongue muscle strength and patient compliance, making it difficult to achieve the absolute stability of micro-implant bone anchorage [4], consistent with the treatment characteristics of physiological anchorage control described in Section 2.2.3.

Correlation analysis revealed a significant positive correlation between the mean SUV of the periodontal ligament and the amount of anchorage loss ($r = 0.78$, $P < 0.001$). This finding has significant clinical implications, indicating that [^{18}F] fluoride PET/CT nuclear imaging technology can provide early warning of the risk of anchorage loss by monitoring periodontal ligament metabolic activity. It offers objective evidence for clinicians to promptly adjust treatment plans and reinforce anchorage, thereby addressing the limitations of traditional assessment methods, which can only monitor changes in tooth position but cannot detect the risk of anchorage loss at an early stage [6]. This aligns with the research background outlined in Section 1.1 regarding “nuclear imaging technology providing a new approach for anchorage assessment” and seamlessly connects with the correlation analysis results in Section 3.1.2.

4.2 Comparison of Orthodontic Outcomes Among Different Anchorage Methods and Their Clinical Implications

The results of this study indicate that there were no significant differences among the three anchorage methods in terms of tooth movement efficiency, improvement in occlusal relationships, and facial aesthetic optimization; all methods achieved good orthodontic

outcomes. These findings are fully consistent with the results presented in Section 3.2 (Tooth Movement Efficiency, Occlusal Relationships, and Facial Aesthetics) and are also consistent with the conclusions of some previous studies [4,7]. Specifically, there were no significant differences among the three groups in terms of the time required to close extraction spaces, the amount of anterior tooth retraction, or the distal movement of the canines. This indicates that regardless of the anchorage method used, efficient tooth movement can be achieved—rapidly closing extraction spaces, retracting the anterior teeth, and improving maxillary protrusion—provided that the magnitude and direction of orthodontic forces are appropriately controlled; Post-treatment, anterior overjet and overbite in all three groups returned to normal ranges, with a reduction in the PAR index exceeding 85% in all cases. The molar relationship was restored to a neutral position, and masticatory function was significantly improved. There were no significant differences in facial aesthetic indicators or aesthetic scores; all methods effectively optimized facial protrusion, improved lip-to-tooth relationships, and met patients' aesthetic expectations, thereby corroborating the core conclusion in the abstract that “there is no significant difference in treatment efficacy among the three anchorage methods.”

These findings suggest that when selecting an anchorage method in clinical practice, practitioners should make personalized choices based on the patient's specific circumstances—such as the severity of the malocclusion, financial situation, aesthetic preferences, and treatment compliance—while ensuring anchorage stability. For complex cases with high anchorage requirements, such as severe maxillary protrusion or multi-tooth movement, micro-implant bone anchorage is the optimal choice. Its absolutely stable anchorage control effectively prevents anchorage loss and ensures the predictability of treatment outcomes [3], consistent with the findings in Section 3.1.2 that “the micro-implant group had no moderate-to-severe anchorage loss”; For patients with moderate anchorage requirements, limited financial resources, or reluctance to undergo invasive procedures, physiological anchorage control is a preferable option. It involves minimal trauma, offers good aesthetics, and achieves acceptable anchorage and treatment outcomes [4], consistent with the therapeutic advantages of physiological anchorage described in Section 2.2.3; Although traditional intraoral anchorage has relatively poor stability, it is simple to perform and cost-effective, making it suitable for cases of mild malocclusion with low anchorage requirements. However, anchorage monitoring must be strengthened during treatment, and traction methods should be adjusted in a timely manner to minimize anchorage loss [1]. This finding corresponds with the result in Section 3.1.2, which reported a “20% rate of severe anchorage loss in the traditional group,” providing clear guidance for clinical application.

4.3 The Value of Nuclear Isotope Detection Technology in the Evaluation of Orthodontic Anchorage

As a non-invasive, dynamic, and quantitative bioimaging technique, [^{18}F] fluoride PET/CT has demonstrated unique advantages in this study. Compared with traditional methods such as cephalometric analysis and plaster model measurements, this technology can detect early signs of anchorage loss by monitoring changes in the SUVmean of the periodontal ligament before significant positional shifts in the anchor teeth occur. This enables dynamic monitoring and early warning of the risk of anchorage loss, providing objective evidence for the timely adjustment of clinical treatment plans [6], which aligns with the research background in Section 1.1 that “nuclear imaging technology can achieve early warning of anchorage loss.” Additionally, this technology enables the quantitative assessment of periodontal ligament metabolic activity, facilitating in-depth exploration of the biological mechanisms underlying anchorage loss and providing theoretical support for the innovation and improvement of anchorage control techniques.

This study established an evaluation system for anchorage stability based on [^{18}F] fluoride PET/CT nuclear imaging technology, clarifying the testing procedures, definition of indicators, and quantification criteria. It filled a gap in comparative studies of the three mainstream anchorage methods using nuclear isotope technology and further expanded the scope of nuclear medicine applications in the field of orthodontics [6]. This is consistent with the statement in Section 1.3 regarding the research significance: “filling the gap in the comparative study of the three main anchorage methods using nuclear isotope technology.” However, this technology also has certain limitations, such as high examination costs and associated radiation exposure, making it difficult to widely implement in primary care hospitals. In the future, the testing protocol could be further optimized to reduce radiation exposure and examination costs, thereby promoting its widespread clinical application and providing a direction for subsequent research.

5. Conclusion

1. [^{18}F]fluoride PET/CT nuclear imaging technology enables dynamic, quantitative assessment of orthodontic anchorage stability by monitoring the mean SUV of the periodontal ligament; furthermore, the mean SUV of the periodontal ligament shows a significant positive correlation with the degree of anchorage loss ($r = 0.78, P < 0.001$), serving as an early warning indicator for the risk of anchorage loss. This provides objective and precise technical support for orthodontic anchorage management, and is fully consistent with the results of radionuclide imaging and correlation analysis presented in Section 3.1.
2. Among the three anchorage methods, micro-implant-based bone anchorage offers the highest stability. Anchorage loss is significantly lower than with traditional intraoral anchorage and physiological anchorage control, and there are no cases of moderate or severe anchorage loss. It is particularly suitable for complex malocclusion cases, such as severe maxillary protrusion, which require high levels of anchorage; Anchorage stability with physiological anchorage is

superior to that of traditional intraoral anchorage; it is minimally invasive and aesthetically pleasing, making it the preferred option for patients with moderate anchorage requirements. Traditional intraoral anchorage can be used for cases of mild malocclusion, but requires enhanced monitoring of anchorage stability, consistent with the anchorage loss data and classification results presented in Section 3.1.2.

3. There were no significant differences among the three anchorage methods in terms of tooth movement efficiency, improvement in occlusal relationships, or facial aesthetic outcomes; all methods achieved good orthodontic results. Clinicians may select the appropriate anchorage method on a case-by-case basis, taking into account factors such as the severity of the patient's malocclusion, financial circumstances, and aesthetic preferences. These findings are consistent with the results of the efficacy assessment in Section 3.2 and the core conclusions of the abstract.

4. All three anchorage methods offer a high level of safety, with a low and manageable incidence of adverse reactions. When properly managed, these reactions do not interfere with the course of treatment, making them suitable for widespread clinical use. These findings are consistent with the adverse reaction results reported in Section 3.3 and further refine the clinical evaluation system for the three anchorage methods.

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