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Research and analysis of orthodontic force

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Abstract: Although contemporary orthodontics has established a relatively complete system, the planning of treatment options and the preparation of orthodontic appliances still heavily rely on the personal experience of orthodontists. However, orthodontists cannot predict the orthodontic force generated by the appliances, leading to frequent follow-up visits and adjustments, which result in a "trial and error" treatment approach. This not only prolongs treatment time and increases treatment costs but also brings additional side effects. Currently, orthodontic treatment in clinical treatment period is long, and side effects are large. Therefore, shortening the clinical treatment time is essential. This article analyzes the biomechanics of orthodontics and discusses the reasonable range of orthodontic forces, aiming to provide reference for shortening the clinical treatment time of orthodontics.

1. Introduction

Malocclusion is one of the major oral health issues that significantly affect human health, with a high incidence rate. In China, the incidence of malocclusion among adolescents and children is as high as 52.8% to 72.9%, reaching 91.2% when compared to ideal normal occlusion[1-3]. Approximately 120 million teenagers in China require orthodontic treatment. However, according to the results of the third national oral epidemiological survey in 2005, less than 10% of patients in China receive orthodontic treatment, which is significantly lower than in developed countries[4,5]. Malocclusion not only affects patients' facial appearance, jaw development, and oral function but may also lead to major cardiovascular and cerebrovascular diseases. Furthermore, it has negative impacts on patients' employment prospects, marriage choices, career advancement, causing severe psychological harm. With the comprehensive development of China's economy and society, there is an increasing demand for orthodontic treatment, yet the current clinical technology falls short of meeting patients' needs. Improving the current state of orthodontic treatment is a goal in the field of oral medicine in China and a medical issue that must be addressed as the country progresses socially[6].

The primary manifestation of orthodontics is tooth movement, fundamentally caused by the reconstruction of alveolar bone. The reconstruction of alveolar bone is related to the stress or strain on the periodontal ligament after applying orthodontic force to the teeth, thereby affecting the effectiveness of tooth correction. To date, in clinical orthodontic treatment, orthodontists still plan a treatment regimen based on their experience and apply devices without any scientific basis. This inevitably leads to misdiagnosis, repeated visits, prolonged orthodontic treatment periods, and may result in serious side effects such as excessive root resorption, increased tooth mobility, and significant psychological stress for patients[7]. This article analyzes the fundamentals of orthodontic biomechanics and discusses the appropriate range of orthodontic force, aiming to provide guidance for orthodontic treatment.

2. Biomechanical basis of orthodontics

2.1 Periodontal structure and biological behavior

When orthodontic forces act on teeth, it causes a series of physiological changes in the periodontal tissues, ultimately leading to the proliferation, differentiation, and apoptosis of periodontal membrane cells, osteoblasts, and osteoclasts, resulting in bone resorption on the pressure side and bone deposition on the tension side of the alveolar bone to achieve the purpose of tooth movement[8]. Therefore, a certain degree of understanding of the structure and biological characteristics of periodontal tissues is necessary. Periodontal tissues, also known as tooth-supporting tissues, mainly consist of the periodontal ligament, alveolar bone, and gingiva. They play a crucial role in protecting and supporting teeth, positioning them in the alveolar socket, and withstanding chewing forces. In the entire orthodontic process, the periodontal ligament and alveolar bone play irreplaceable roles, so the biological characteristics of the periodontal ligament and alveolar bone will be mainly discussed below.

2.1.1 Biological behavior of the periodontal membrane

The periodontal ligament, also known as the periodontal membrane, is composed of dense fibrous tissue that surrounds the tooth root, located between the tooth bone and the tooth socket. It mainly consists of various types of cells, matrix, nerves, and collagen fibers, with the tooth anchored in the tooth socket by fibers made of type I collagen. These fibers act to cushion and distribute external forces, as well as withstand chewing pressure[9].

To date, the exact role of the periodontal ligament in the process of tooth movement is not fully understood. However, its unique biomechanical, cellular, and molecular properties undoubtedly play a crucial role in understanding clinical orthodontic tooth movement. When orthodontic forces are applied to the teeth, the periodontal ligament first senses tissue changes and then transmits them to the alveolar bone, prompting corresponding tissue remodeling and ultimately leading to tooth movement. This mechanical signal sensing and transmission function is primarily carried out by the fibroblast cells in the periodontal ligament.

From a biomaterial perspective, the material properties of the periodontal ligament exhibit nonlinearity and time-dependent viscoelasticity, playing an irreplaceable role in controlling the deformation area of the periodontal ligament and tooth movement under orthodontic forces. Therefore, when subjected to mechanical forces, it undergoes rapid displacement followed by extremely slow movement, completing maximum displacement after several hours. This suggests that the liquid component in the periodontal ligament may play an important role in the transmission and regulation of orthodontic forces.

During clinical orthodontic treatment, the periodontal ligament exhibits a complex biological behavior under orthodontic forces, involving responses to orthodontic forces at tissue, cellular, molecular, and genetic levels. Here, we will mainly focus on its tissue and cellular levels.

At the organizational level, there are mechanoreceptors and nociceptors on the nerve endings of the periodontal ligament, which are normally in a static state. However, when orthodontic forces act on the teeth, this static state is disrupted, leading to an active perception of the stress and strain in the periodontal ligament. This information is then transmitted, triggering a series of physiological responses in the periodontal tissues. On the tension side of the periodontal ligament, there is thickening and widening of the membrane, dilation of capillaries, rearrangement of fibroblast cells, increased number of connective tissue cells, and activation of certain cells, leading to bone deposition in the corresponding alveolar region. On the compression side of the periodontal ligament, the membrane thickness decreases, the alveolar process deforms, and different degrees of pressure result in various tissue responses, with mild pressure inducing direct bone resorption and heavy pressure causing a transparent change in the periodontal ligament followed by bone resorption.

At the cellular level, the periodontal ligament, located in the gap between the tooth root's cementum and the alveolar socket, is subjected to periodic and varying pressures, tensions, and shear forces, leading fibroblast cells to constantly perceive and transmit mechanical signals to the periodontal tissues, thereby inducing tissue remodeling. The unique biomechanical characteristics of the periodontal ligament stem from the opposing activities of cell proliferation and apoptosis in response to stress.

2.1.2 Biological behavior of alveolar bone

The alveolar bone, also known as the alveolar process, is the part of the upper and lower jaw bones that surrounds and supports the tooth roots. It can be divided into intrinsic alveolar bone, compact bone, and cancellous bone based on its anatomical cross-sectional structure. The alveolar bone is highly plastic, changing with the growth and development, shedding and replacement of teeth, as well as chewing pressure. It undergoes continuous remodeling due to tooth movement, exhibiting characteristics of compression absorption and tension generation. The part connecting to the tooth root is called the alveolar socket, which supports and fixes the teeth, withstands orthodontic forces, and plays a crucial role in alveolar bone remodeling.

The material properties, microstructure, and morphology of bones determine their mechanical characteristics, serving as the material basis for bone physiological activities. Bone function, in turn, determines bone shape and structure. Therefore, exploring the mechanical properties of alveolar bone requires a comprehensive consideration of its tissue structure, morphology, and function. The mechanical characteristics of alveolar bone exhibit significant anisotropy and inhomogeneity. When significant changes occur in its tissue structure and physiological function, corresponding mechanical properties also undergo significant changes.

Alveolar bone contains receptors that sense external mechanical stimuli and receive signals transmitted by the periodontal ligament, activating relevant cells to induce bone resorption or deposition, a process known as alveolar bone remodeling. At the tissue level, in order to withstand chewing pressure under normal physiological conditions, the arrangement of alveolar bone structure and bone trabeculae must adhere to the principles of mechanics. Changes in external conditions lead to alterations in the structure and arrangement of alveolar bone trabeculae. These transformations illustrate the process of alveolar bone remodeling and indicate that a balance between bone resorption and deposition will ultimately be achieved, involving complex physiological regulatory factors throughout the entire process.

From the cellular level, when orthodontic force is applied to teeth, it will damage the bone tissue in the alveolar socket, and then cause the differentiation and activation of osteoclasts, and eventually lead to bone resorption on the compression side. Alternatively, mechanical stress at the alveolar socket induces accelerated apoptosis of osteoblasts on the compressive side, while osteoclasts are unaffected or only slightly affected, resulting in the disruption of the balance of bone resorption and bone deposition, leading to significant bone resorption on the compressive side. On the strained side, due to the excessive deformation of the periodontal membrane, osteoblasts are activated and bone deposition is induced.

2.2 The structure and biological behavior of teeth

Teeth are the hardest tissues in the human body, consisting of the crown, neck, and root. The crown is used for chewing, while the root is anchored in the alveolar socket to support the tooth. Teeth are primarily composed of enamel, dentin, and pulp, with enamel being the outermost layer. Understanding the material properties of teeth is essential during orthodontic treatment, as teeth are subjected to external factors and the periodontal ligament during the process. Dentin is made up of dentinal tubules and matrix, while enamel consists of enamel rods and interrod enamel, with a distinct interface between dentin and enamel. Enamel exhibits non-isotropic mechanical properties, while dentin shows isotropic properties, leading to an overall isotropic nature of teeth. When teeth are subjected to orthodontic forces, slight bone resorption occurs on the pressure side, but the bone quickly regenerates once the force is removed, indicating that bone damage does not occur within normal physiological limits.

For dental pulp, its main function is to differentiate into odontoblasts. When the orthodontic force is appropriate, a certain pressure is formed at the apex of the tooth root, which may cause mild congestion of the dental pulp. Under a microscope, blood vessels can be observed to dilate, appearing dendritic, filled with blood cells, or showing local vacuolar changes. Generally, there are no lesions clinically, and recovery is possible once the orthodontic force is removed. However, excessive force can lead to pulp edema and even necrosis.

In clinical treatment, root resorption is an unavoidable topic, which can be classified as mild, progressive, or idiopathic resorption. Mild resorption is localized and superficial, with minimal impact. Progressive resorption is continuous and often occurs at the apex of the root, being observable and controllable. Idiopathic resorption, on the other hand, is uncontrollable and irreversible, with rapid root resorption and unknown causes.

The degree of root resorption is related to the direction and magnitude of orthodontic force, duration of action, and type of tooth movement. When orthodontic force acts on the teeth, the periodontal ligament undergoes a biochemical reaction. In this process, substances that corrode the tooth root are inevitably produced. However, due to capillary blockage, these substances cannot be removed and accumulate between the tooth root surface and the periodontal ligament, leading to root resorption. If the orthodontic force is excessive, causing transparency changes in periodontal ligament cells and a significant increase in necrotic areas, root resorption will be more severe.

3. Analysis and research of reasonable orthodontic force

In orthodontic treatment, various factors can influence the movement of teeth, some of which are known, such as the magnitude and direction of orthodontic forces, the health of the teeth, and individual genetics, while others remain unknown. Based on the experience of orthodontists and analysis of the entire process of tooth movement during orthodontic treatment, it is evident that the controllable factors for orthodontists mainly include the position and structure of brackets, the shape of archwires, and the relationship between archwires and brackets. Therefore, it is essential to explore the reasonable range of orthodontic forces.

3.1 Bracket and bow wire

The bracket is one of the main components in clinical orthodontic treatment, directly bonded to the surface of the tooth crown with adhesive, and various types of orthodontic loads come from the interaction between the archwire and the bracket. Its main structural features include a horizontal slot in the middle of the bracket, used to accommodate the archwire. Depending on the depth and width of the slot, it can be divided into two types: one with a depth of 0.7112 mm and a width of 0.5588 mm; the other with a depth of 0.6350 mm and a width of 0.4572 mm, each type of bracket is used with a corresponding type of archwire. Furthermore, brackets can be classified based on their structure as single brackets or twin brackets. Twin brackets have a larger contact area with the archwire, making it easier to correct tooth rotation, which is why twin brackets are frequently used in current clinical orthodontic treatment.

Archwires that are held in the bracket slot or passed through a tube with a ligature are called orthodontic archwires. From a material perspective, they can be categorized as stainless steel archwires, nickel-titanium alloy archwires, and beta-titanium alloy archwires, as well as fiber-reinforced composite archwires. In terms of cross-sectional shape, archwires can be round or rectangular; they can be single-stranded or multi-stranded braided in terms of formation. Additionally, there are several different models based on cross-sectional dimensions. Stainless steel archwires and nickel-titanium alloy archwires have always been the most widely used archwires in clinical orthodontic treatment, with single-strand archwires being predominantly used, while multi-strand archwires have largely phased out of orthodontic clinical treatment applications.

3.2 Reasonable orthodontic force

Throughout the history of orthodontics, the concept of optimal orthodontic force has always been a topic of great interest at every stage of development. Over the past 80 years, the concept of optimal orthodontic force has undergone significant changes. As early as 1932, Schwarz proposed the concept of optimal orthodontic force, defining it as the force that causes the periodontal ligament's pressure stress to approach its normal capillary blood vessel value when external mechanical loads are applied. On the compressed side of the periodontal ligament, no capillary blockage occurs, making this force the optimal orthodontic force. Exceeding the optimal orthodontic force can lead to tissue necrosis and hinder alveolar bone resorption. Tooth movement only occurs once the necrotic cells disappear, during which time the teeth remain immobile.

The current concept of optimal orthodontic force is based on the assumption that forces of a certain magnitude and time characteristics (continuous vs. intermittent, constant vs. variable, etc.) can maximize the rate of tooth movement without causing tissue damage or significant discomfort to the patient. The optimal orthodontic force varies for different individuals and different teeth.

In orthodontic clinical treatment, the magnitude and direction of orthodontic loads are relatively controllable compared to other factors. Analyzing the entire clinical orthodontic treatment process, orthodontic loads first act on the tooth crown and then transfer to the entire periodontal tissue, generating strain and stress in the periodontal ligament. Most scholars believe that the periodontal ligament plays a crucial role in tooth orthodontics, emphasizing the close relationship between optimal orthodontic force and the stress condition of the periodontal ligament.

There is a linear relationship between tooth movement rate and periodontal ligament strain (0.03%~0.3%), as shown in the following formula [10], depicting the linear relationship as shown in Figure 1.

$$r = \begin{cases} 0.0414\left(\varepsilon > 0.3\%\right) \\ 0.153\varepsilon - 0.0046\left(0.03\% < \varepsilon \leq 0.3\%\right) \\ 0\left(\varepsilon \leq 0.03\%\right) \end{cases}$$

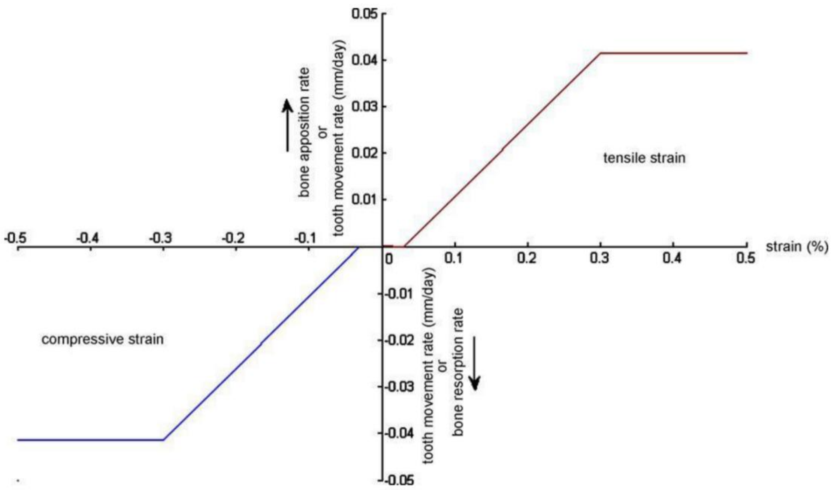

Figure 1: Ideal linear relationship between periodontal membrane strain and tooth movement rate

4. Conclusion

In the clinical treatment of orthodontics, before analyzing and simulating the reasonable orthodontic force and movement modulation of teeth using finite element method, it is necessary to understand the biological characteristics of teeth and periodontal tissues, as well as their respective responses to orthodontic forces. This helps to provide partial index parameters for subsequent research on reasonable orthodontic forces and teeth movement modulation, making the analyzed data more reliable and instructive. This study analyzed the biomechanics of orthodontics and discussed the reasonable range of orthodontic forces, which can provide reference for orthodontic treatment.

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