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Review

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Material properties of periodontal ligaments

Właściwości materiałowe więzadeł przyzębia

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Summary

The mechanism of orthodontic teeth movement is not entirely explained. The principal reaction on tissues at the cellular and molecular level is initiated by the force applied to the tooth crown and transferred in turn upon the periodontal ligament (PDL). It seems, therefore, that the PDL and particularly its properties play a key role in bone remodelling. One of the more commonly used methods, which is capable of analysis of a wide range of orthodontic movements or distribution of stress and strain within teeth and periodontium, is the finite element method (FEM). Aiming to achieve the FEM model as close as possible to *in vivo* conditions, it is necessary to account for accurate material properties. The aim of the present study is to compare particular studies and descriptions of material characteristics of the PDL.
The analysis of available articles shows how imperfect modern descriptions of PDL material properties available today are, which in the precise method could allow the analysis of the occurrences within the *in vivo* processes in a non-destructive manner. The complicated anatomy and physiology of PDL, which incur significant parameter changes with age and disease susceptibility, make the accurate description of this material so difficult. The available study results show that those characteristics should be precise and complicated, which undoubtedly impedes the calculation processes but generates reliable results.

Key words: **FEM • material properties • PDL • bone remodelling • orthodontic forces**

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Introduction

The forces that are applied to the tooth are in turn transferred to periodontal tissues – which include the periodontal ligament (PDL) and the alveolar bone. The positional change of individual teeth is based on those fundamental mechanisms of bone tissue remodelling – resorption and apposition. The mechanism of teeth movement however is not entirely explained. The principal reaction on both tissues at the cellular and molecular level is initiated by the force applied to the tooth crown and transferred in turn upon the PDL. It seems, therefore, that the periodontal ligament and particularly its properties play a key role in bone remodelling [3]. From the anatomical point of view, PDL is a structure which consists of collagen fibres (53-47%), blood vessels and ne-

Table 1. Material properties of periodontal ligament (PDL)

Elastic modulus (MPa)	Poisson's Ratio	Tooth	Species	References
0.5-99.8	0.45	Maxillary canine	Human	[19]
6.8x10-2	0.49	Mandibular canine	Human	[6]
6.66x10-1	0.49	Maxillary central incisor	Human	[29]
1. 0.68 2. Anisotropic 0-10	0.49	Maxillary central incisor	Human	[25]
6.67	4.5	-	-	[30]
50	0,45	Maxillary incisors	Human	[15]
6.90x10-1	0.45	Maxillary central incisor	Human	[27]
Bilinear	0.3	Canine	Dog	[16]
Non-linear	0.45	Mandibular first molar	Human	[13]
0.75	0.45	Mandibular premolar	Human	[21]
0.01-0.03	0.45-0.49	Maxillary incisor	Human	[23]
0.667	0.49	Maxillary central incisor	Human	[10]
Bilinear	0.3	First molar	Rat	[17]
1	0.45	Maxillary incisor, canine	Human	[5]
6.8x10-2	0.49	Maxillary dentition	Human	[4]
0.01; 0.1; 1	0.45	Mandibular first premolar	Human	[8]
Bilinear	0.3	Premature molar	Pig	[33]
-	0.3	Incisors, canine	Human	[24]
1. 0.17 (linear high model) 2. 0.044 (linear low model) 3. Non-linear	0.45	Mandibular canine, premolar	Human	[3]
0.1	0.45	Maxillary first premolar	Human	[14]
0.7	0.49	Molar	Rat	[11]
Bilinear	0.3	-	-	[7]

rve endings (1-2%) that are embedded in an amorphous mucopolysaccharide matrix [9]. It is impossible to evaluate experimentally, *in vivo*, the distribution of stress and strain exerted within the tooth and periodontium during active orthodontic treatment. Therefore, one can find in the literature cases involving the evaluation of those parameters *in vitro*. For this purpose, various types of measuring methods, for example laser holography [2], optoelectronical set-ups [12], photoelastic models [18] or electronic speckle pattern interferometry (ESPI) [7] are utilized. One of the more commonly used methods, which is capable of analysis of a wide range of orthodontic movements or distribution of stress and strain within teeth and periodontium, is the finite element method (FEM). Aiming to achieve the FEM model as close as possible to *in vivo* conditions, and only such a model allows the collection of reliable results, it is necessary to account for accurate material properties. However, by reviewing the available literature we can find examples of different measuring methods or different materials, thus making the specification of ideal characteristics extremely difficult.

The aim of the present study is to compare particular studies and descriptions of material characteristics of the PDL which are used in articles that analyse teeth positional movements induced by orthodontic forces.

Articles were identified by searches of the following databases: EMBASE, MEDLINE, PubMed, Scopus. The following search terms were used: "finite element analysis", "finite element method", "mechanical properties", "elasticity", "nonlinear elasticity", "orthodontic tooth movement", "periodontal ligament (PDL)".

A comparison of material properties is shown in table 1. One of the describing properties of PDL is Poisson's ratio, whose value ranged in individual studies from 0.3 to 0.49 MPa (table 1). The studies conducted in the 1990s recognised PDL as a linear, isotropic and elastic material [6,10,15,19,21,27,29,30]. Worth noting is the fact that even today there are articles published which use such characteristics [5, 8]. Cattaneo et al. however, using very precise data concerning PDL anatomy, gained from computed microtomography, proved that PDL is anisotropic tissue with strong nonlinear characteristics. Moreover, the studies of Cattaneo et al. showed that the material properties of PDL have a strong influence on the transfer of orthodontic forces. Vollmer et al., Provadis, Poppe et al., and Pietrzak et al. also came to similar conclusions in their studies [23,24,25,31].

Discussion

Bone remodelling engages a complicated net of interactions between cells from the osteoblast line, hormones, and locally produced cytokine and growth factors [20]. It is not difficult to agree with the impression that orthopaedic and orthodontic concepts concerning bone remodelling have a lot in common. Both require the understanding of bone biology and in particular the relation between mechanical stress and strain and various types of cells. Orthodontic teeth movements however seem to be a slightly more complicated process, which requires remodelling not only within alveolar bone but also within the PDL.

The significant differences in the description of the material characteristics of PDL are probably caused by many factors. Undoubtedly there are various measuring methods used, for example compression, extension, pressure or ultrasound. In each of these methods, the differences are noticeable depending on value, time, direction of the applied force or the frequency in the ultrasound method. Furthermore, also extremely significant seems to be the material studied. As the above-mentioned literature review revealed, studies conducted evaluate not only human PDL but also those of animals such as rats [11, 17] or pigs [33]. The animal material does not exactly reflect the properties of human tissue because of differing anatomy and metabolism. Furthermore, the differences also concerned those between human teeth types – premolar [8, 14, 21], molar [13], incisor [10, 27], and canine [5, 16] or full dentition [4]. Also important to consider seems to be the individual factors of each instance – the root of each tooth has a slightly different length and shape, which influences the PDL magnitude. The next significant factor is the humidity of the material because different results are gained when the material properties are determined using dry samples or physiologically wet samples.

Despite many publications concerning the analysis of orthodontic teeth movement within the alveolar bone being present, it is difficult to resist the conclusion that the material properties of the PDL are the Achilles' heel of these studies. The articles published in prestigious journals over the last 30 years very often give completely different properties and are sometimes simply excluded. In many articles there is a lack of detailed description regarding how the analysed material was harvested, prepared or loaded. Insufficient description of the methodology sometimes prevents identification of whether the material properties were gained from original studies or taken from other sources, which may indicate identical features in different studies.

Conclusions

The analysis of available articles shows how imperfect modern descriptions of PDL material properties available today are, which in the precise method could allow the analysis of the occurrences within the *in vivo* processes in a non-destructive manner. The complicated anatomy and physiology of PDL, which incur significant parameter changes with age and disease susceptibility, make the accurate description of this material so difficult. If the authors analyse the processes occurring in the whole cranium or craniofacial complex, the modelling of this complicated structure, namely PDL, may be even ignored [1, 21, 26, 28, 32]. However, if we want to analyse the movement of a single tooth within the alveolar bone in both patients with a healthy periodontium and periodontally compromised ones, precise modelling of the PDL with an account of all of its features is necessary. The available study results show that those characteristics should be precise and complicated, which undoubtedly impedes the calculation processes but generates reliable data.

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