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PERIODONTAL LIGAMENT MAY BE VIEWED AS A POROUS MATERIAL FILLED BY FREE FLUID: EXPERIMENTAL PROOF

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Abstract. The purpose of this investigation is to show experimentally that there are the ways for fluid movement in the periodontal ligament and that the periodontal ligament fluid may flow under pressure. In addition, the permeability coefficient of the periodontal ligament involved in the Darcy's law equation is estimated. It turns out to be in the order of $10^{-8}\ \mathrm{m}^2/(\mathrm{Pa}\cdot\mathrm{sec})$. Therefore such a structure of the periodontal ligament might help to illuminate the nature and the mechanism of one of the main periodontal ligament functions, i.e. providing tooth support under load.

Key words: periodontal ligament, periodontal fluid, porous medium containing a fluid, Darcy's law, permeability coefficient, experiment

Introduction

The periodontal ligament (PDL) is a dense connective tissue that surrounds the root of the tooth and attaches it to the alveolar bone.

The PDL plays a broad spectrum of functions. The primary functions are providing tooth support and blood supply. There is no disagreement concerning the role of the PDL in providing support for the teeth, but there is considerable controversy involving the mechanism by which this function is accomplished. The precise sequence of events that occurs in the PDL when force is applied to a tooth is not known [1].

Such a multifunction of the PDL depends upon its complex structure. The PDL consists mainly of collagen fibers, most of them being arranged into fiber bundles. Collagen fibers comprise 50% of the PDL by weight. Furthermore, the PDL also contains considerable amount of cells, nerves, vasculature, interstitial fluid.

To explain the mechanism of tooth support by the PDL we believe that the PDL must biomechanically be considered as a porous solid (collagen fibres, walls of blood and lymphatic vessels) containing a fluid (interstitial fluid, blood, lymph). In Fig.1 are shown the collagen fiber bundles of the rat's molar [2].

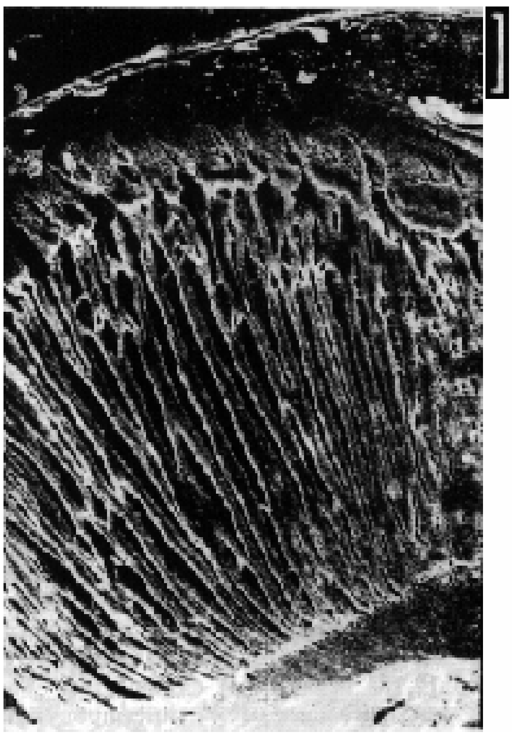

Fig.1. The PDL of the rat's molar. (Scale of 100 μm) [2].

Lowney et al. [3] studied the influence of orthodontic forces on the amount of cytokines in the periodontium before and after the application of an orthodontic force. They assumed the orthodontic forces to induce the movement of the PDL fluid and, with them, any cellular biochemical product produced from prior mechanical perturbation. As illustrated schematically in Fig.2, the direction of the PDL fluid may be as follows: from an area of compression, to an area of tension, both apically and coronally, toward the gingival sulcus, and/or into the alveolar marrow spaces.

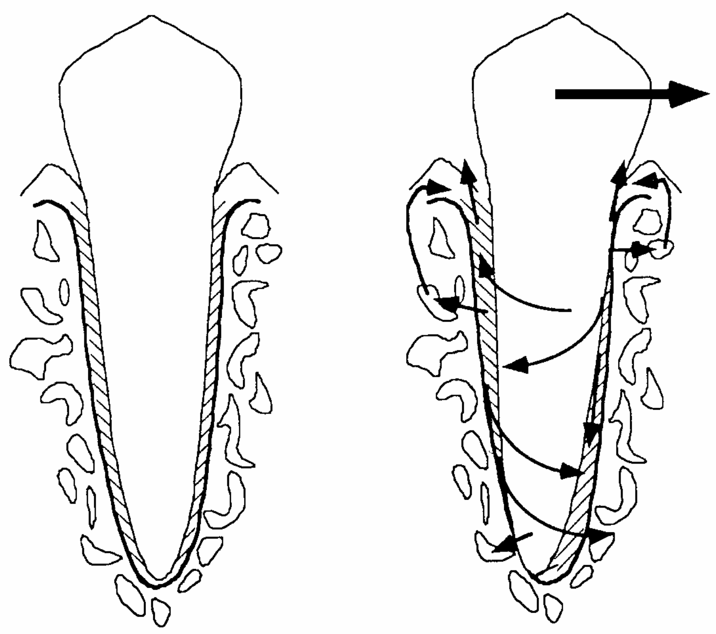

Fig.2. Diagram of tooth before and at the instant of the force application. Arrows show probable pathways of the PDL fluid. These include the PDL, the marrow spaces, and the gingiva, as well as the sulcus area [3].

In this investigation, we assumed that a part of fluid constituent of the PDL may be free under the certain conditions and this fluid may move within the PDL under pressure gradient due to particular arrangement of the bundles and the walls of vessels.

If this hypothesis is borne out, then we can make the inference that it is fluid which is incompressible that provides a relevant stiffness of the PDL. Moreover in this case fluid displacements cause as uniformity of load distribution when a force is applied to the tooth as reversibility of strains occurring when a force is removed.

To test this hypothesis the experiment was developed and made on guinea-pigs. It was suggested to inject with a blue dye under pressure into the certain zone of the PDL. As a result the nonuniform distribution of the PDL fluid pressure occurs and the PDL fluid may move under pressure gradient within the PDL. It may result in turning of the PDL and the tooth's root on the opposite side from the injection zone to a blue colour.

Materials and methods

Five guinea-pigs were used in the experiment. Fig.3 illustrates appearance of an animal and Fig.4 does mandibular incisors (one of them was put to experiment).

Each animal was anaesthetised and sacrificed. Then the mandible was extracted and the face skin, muscles and other soft tissues were dissected from the mandible (Fig.5).

As a dye, the 1% solution of cyanolum (blue colour) was used for it fulfilled the necessary experiment requirements. The dye was dissolved in the isotonic solution (0.9% solution of NaCl in water). Moreover, due to its small sizes (less than 1 nm) the dye might move together with the solvent (the PDL fluid) within the porous medium of the PDL.

The dye solution was injected by syringe into the PDL through the circular ligament of the incisor.

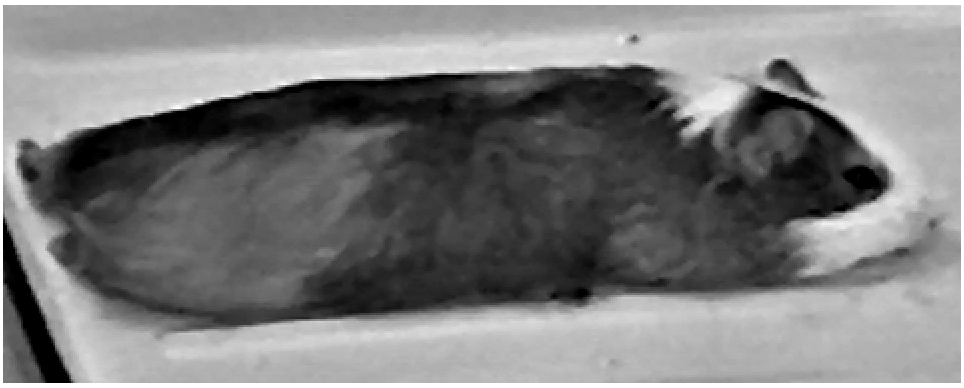

Fig.3. Appearance of a guinea-pig.

Fig.4. Mandibular incisors.

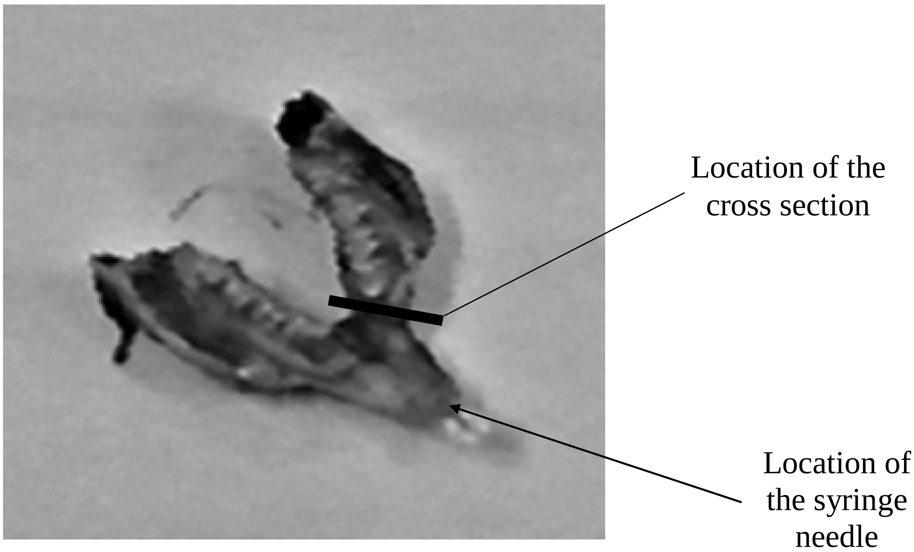

Fig.5. The mandible after removing of the soft tissues on it.

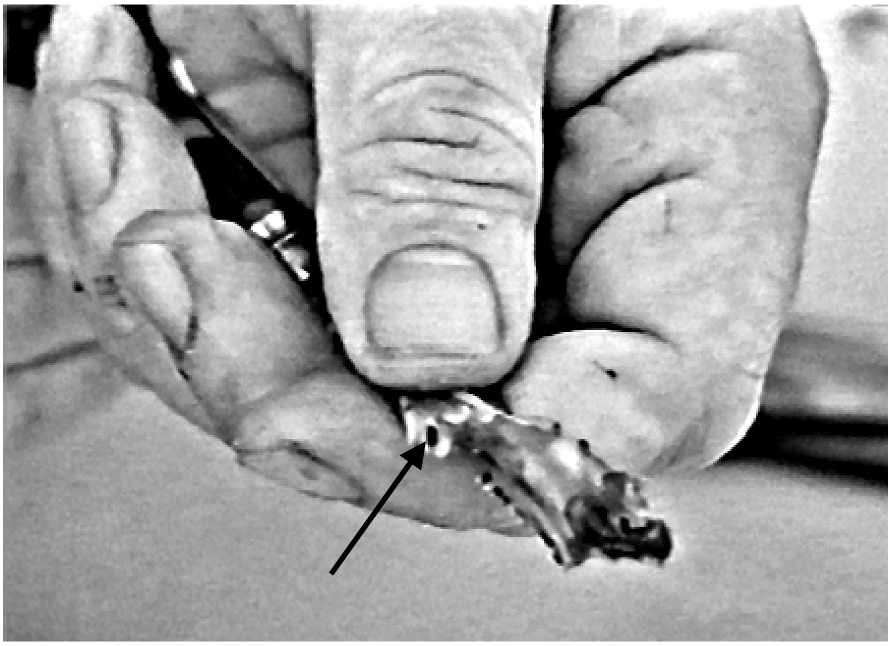

Fig.6. The cross section (shown by arrow) before the dye injection.
A dark spot in the middle of the cross section is the pulp region.

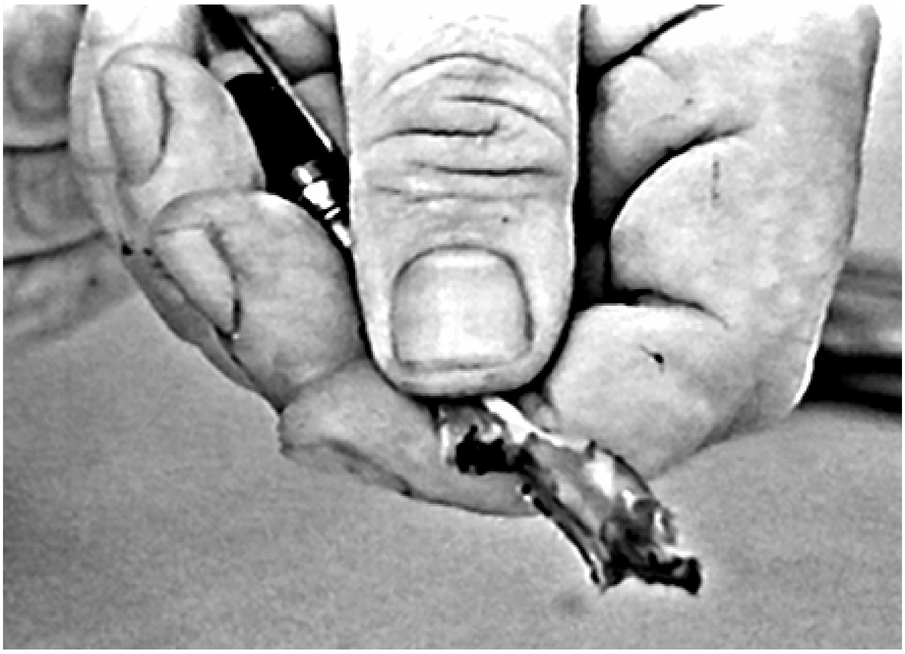

Fig.7. Idem, at the instant of turning of the cross section to a blue colour.

Note that the shape and the location of the guinea-pig’s incisor are significantly different from those of the human one. However the PDL of both of them must perform the same function, namely absorption of mechanical load. It is beyond reason to think that the load transformation mechanism in the human PDL differs from one in the guinea-pig's PDL.

Because the root of the guinea-pig’s incisor is located along a large share of the mandible, then the apical part of the root was removed. Further the resultant cut surface will be called the “cross section” (Fig.5).

It should be emphasized that since the dye was injected no later than 5 minutes after the animals were sacrificed, then it can be said with assurance that the PDL did not undergo any transformations.

Results of the experiment

It was recorded that within 1-2 sec after the dye injection the blue fluid exuded from the PDL and covered the cross sections of all the animals. In Fig.6 is shown one the tested fragments before the dye injection. In Fig.7 is shown this fragment at the instant of turning of the cross section to a blue colour.

This result supports to the view that the PDL fluid moves within the PDL under pressure gradient. Notice that the dye solution may move only together with a free fluid. Hence it follows that a part of fluid constituent of the PDL must be free under the certain conditions.

It should be pointed out that the dye solution movement was convective rather than diffusive, i.e. the dye solution moved in accordance with pressure gradient (together with the PDL fluid) rather than in accordance with concentration gradient. The reason is that connective process is the faster of the two. Moreover, it has been found experimentally that time of dye appearance on the cross section after the beginning of pressure application to the syringe plunger depends on pressure magnitude.

Estimation of the permeability coefficient of the PDL

The experiment enables the permeability coefficient of the PDL to be estimated. This coefficient *k* is involved in the equation of Darcy’s law of fluid filtration [4]:

$$\mathbf{v}=-k\vec{\nabla}p\,. \qquad (1)$$

where $\mathbf{v}$ is the velocity of fluid filtration,

$\vec{\nabla}p$ is the fluid pressure gradient.

Measurements of pressure to the syringe plunger during the dye injection were taken. A blue fluid turned out to appear on the cross section within t=1-2 sec after application of pressure p_o=50-100 mmHg (6.66-13.33 kPa), the mean distance of the needle top of a syringe to the cross section being ℓ=1 cm (Fig.8).

To estimate the permeability coefficient of the PDL consider one-dimensional fluid filtration in the x direction (Fig.8).

Then the equation (1) yields:

$$\text{v}=-k\frac{\partial p}{\partial x}\,. \qquad (2)$$

Upon integrating of equation (2) at a constant velocity of fluid filtration we obtain:

$$k=\frac{\ell^2}{p_\circ t}. \qquad (3)$$

Substitution of experimental data into the equation (3) gives the permeability coefficient of the PDL to be in the order of 10^{-8} $\mathrm{m^2/(Pa\cdot sec)}$. For comparison, the permeability coefficient of the intervertebral disc equals 10^{-14} $\mathrm{m^2/(Pa\cdot sec)}$ [5], the permeability coefficient of the articular cartilage does 2.65 10^{-14} $\mathrm{m^2/(Pa\cdot sec)}$ [6].

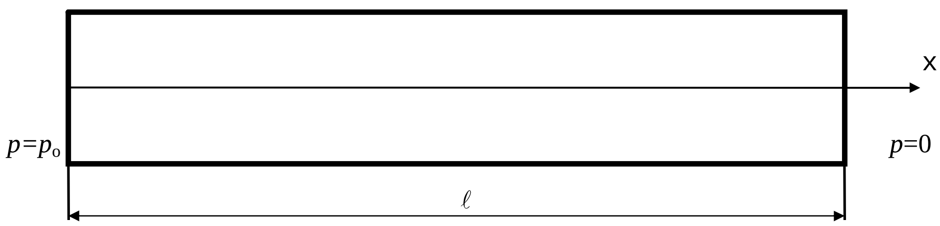

Fig.8. One-dimensional fluid filtration model. Notation: $p=p_o$ is the fluid pressure in the syringe (left); p=0 is the fluid pressure on the cross section (right), ℓ is the distance of the needle top of a syringe to the cross section.

Conclusions

It was experimentally shown that the PDL structure allowed the PDL fluid to move under pressure gradient within the PDL. From the results obtained it may be concluded that a part of fluid constituent of the PDL must be free under the certain conditions.

Moreover the experiment provided to estimate of the permeability coefficient of the PDL. It proved to be in the order of 10^{-8} $\mathrm{m^2/(Pa\cdot sec)}$.

We think that consideration of the PDL as a porous solid containing a free fluid might help to furnish insights into the mechanism and the nature of the providing tooth support under load by the PDL as well as other functions of the PDL.

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Периодонт как пористая среда, насыщенная свободной жидкостью: экспериментальное доказательство

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В эксперименте показано, что структура периодонта позволяет периодонтальной жидкости перетекать из зон с повышенным давлением в зоны с пониженным давлением. На основании выявленных фактов можно считать, что при определенных условиях хотя бы часть периодонтальной жидкости может находиться в свободном (т.е. не связанном, например, макромолекулами или не ограниченном другими тканями) состоянии.

В результате соответствующих измерений в настоящей работе также была сделана оценка коэффициента проницаемости периодонта, входящего в закон Дарси. Для случая одномерной фильтрации жидкости оказалось, что коэффициент закона Дарси для периодонта имеет порядок 10^{-8} $м^2/(Па \cdot сек)$, то есть коэффициент проницаемости периодонта имеет порядок 10-11 $м^2$.

Отметим, что полученный факт о возможности перемещения жидкости в периодонте важен для клиники, так как объясняет процесс амортизации нагрузки периодонтом. На основании полученных данных можно сделать вывод, что амортизация обеспечивается не только коллагеновыми волокнами, но и жидкостью. Библ. 6.

Ключевые слова: периодонт, периодонтальная жидкость, пористая среда, закон Дарси, коэффициент проницаемости, эксперимент

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