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QUOTIENTS OF LONGITUDINAL STABILITY FOR DENTAL IMPLANTS

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Abstracts. A concept of longitudinal stability is introduced for dental implants. It is well known that the *Osstell ISQ* device (Implant Stability Quotient, Sweden), along with forced oscillations of dental implants arising under lateral loads, may also excite longitudinal oscillations and register their resonance frequency. The objective of the study is to substantiate possibility to apply quotients of longitudinal stability in order to assess readiness of dental implants for functional loads, as well as to verify methods of their measurement using the *Osstell ISQ* device by comparison with appropriate quotients of longitudinal rigidity measured by laser testing. In comparison with the traditional technique, the proposed one has a number of advantages and enables creation of a new and more perfect base for noninvasive monitoring of dental implant osteointegration process. For example, the use of modified “magnetic plugs” instead of magnetic pins (SmartPeg) allows quotients of longitudinal stability to be measured through a mucous membrane of alveolar bone, i.e. a dental implant will not be open for further use as a fixed denture support, and modified “magnetic caps” allow determination of quotients of longitudinal stability for spherical headed mini implants used for additional fixation of detachable dentures when teeth are absent totally. Please note that the traditional *Osstell ISQ* technique does not enable measurements of coefficients of stability for the said mini implants. Introduction of quotients of longitudinal stability has made it possible to create a simple theoretical model of oscillations for dental implants fixed in elastic and viscous-elastic medium, to relate quotients of longitudinal stability and longitudinal rigidity to each other, and to assess bearing capacity of dental implants. Moreover, recommendations remain the same when assessing implant readiness for functional loads using quotients of longitudinal stability since the ratio of quotients of stability for longitudinal and lateral loads approximates unity.

Key words: prosthetic dentistry, dental implant, mini dental implant, quotient of stability, quotient of rigidity.

INTRODUCTION

In recent years, the resonance frequency analysis has become one of the main (mechanical) criteria of dental implant readiness for functional loads. A reliable assessment of implant osteointegration level is of crucial importance in selection of denture structure, functional loading tactics, as well as in forecast of orthopedic treatment results. In that respect, enhancement of the *Osstell ISQ* (Implant Stability Quotient) device by use of quotients of longitudinal stability (ISQ_b) can hardly be overestimated.

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The possibility to use the *Osstell mentor* device in the dental implant longitudinal oscillation excitation mode and record the appropriate resonance frequencies was noticed after a business trip of our graduate student to Gothenburg (Sweden) in 2008 where he measured dental implant quotients of stability under the direction of *Osstell AB* employees, and they did not recommend him to measure ISQ_b. Nevertheless, that research went on, quotients of longitudinal stability ISQ_b and longitudinal rigidity K_b were related to each other, and the direction itself appeared to be very fruitful. Hereinafter, we shall have to deal with several quotients of stability and rigidity, so let us introduce the following symbols: for lateral loads on dental implant directed along dentition, we shall use τ index for quotients of stability and rigidity (ISQ_τ, K_τ); for loads directed across dentition – *n* index (ISQ_n, K_n); for those directed along implant axis – *b* index (ISQ_b, K_b).

For the first time, quotients of lateral stability (ISQ_n) for dental implants measured by the *Osstell mentor* device (Sweden) were compared with quotients of lateral rigidity K_n measured by laser testing (Institute of Mechanics of Moscow State University) in 2008, and the most of ISQ_n measurements was made in Gothenburg by Swedish operators [13]. That study demonstrated that readings of the *Osstell mentor* instrument were well correlated with quotients of rigidity measurements in the main range of change ($55 < ISQ < 85$). But when rigidity of dental implant fastenings in osseous tissue analogs reduced, the spread in values considerably increased, and the behavior asymptotics for quotients of stability *ISQ* was incorrect when quotients of rigidity tended to zero ($K_n \to 0$). Such weaknesses were removed in a new version of the *Osstell ISQ* device.

A large series of experiments made by us on 4 devices of the *Osstell ISQ* version demonstrated the correct asymptotics (quotients of stability were small for small values of quotients of rigidity). We should note that for values of quotient of lateral rigidity $K_n > 0.5$ MN/m (quotients of lateral stability $ISQ_n > 50$), the observed data obtained for two different versions of the device did not practically differ (the difference was within the error rate).

This paper studies the latest version of the *Osstell ISQ* device and verifies it by comparison of quotients of longitudinal stability ISQ_b and quotients of longitudinal rigidity K_b, as well as describes new capacities of the device in comparison with the traditional measurement technique.

Materials, devices, and measurement methods

During the research, we used classical screw-type dental implants from Conmet Company (Russia) and mini implants from 3M ESPE Company (USA) fixed in osseous tissue analogs of solid-foamed material, polyurethane, linden, and boxyl. The shape, dimensions, and mass of implants are shown in paper [9].

Quotient of longitudinal rigidity K_b was measured by laser testing and introduced as the ratio of longitudinal force *F* to the appropriate implant translational movement along the symmetry axis:

$$K_b = F/\Delta ,$$

where *F* is force along the implant axis, Δ (in microns) is implant movement (the quotient of lateral rigidity shall be determined similarly: $K_n = F/\Delta$, but here *F* is lateral force and Δ is the movement of the load application points to the dental implant.

Let us assume that implants are completely rigid and only move due to elastic properties of osseous tissue. Fig. 1 shows the measurement design for quotients of longitudinal rigidity, where *1* is screw implant, *2* is osseous tissue analog. Pin *3* supported by dental implant is loaded by force *F*. It is rigidly connected with lever *4* rotating around the axis passing through *O* point. The point of beam fall of laser *5* fixed to *OA* lever makes movement ξ on screen *6*.

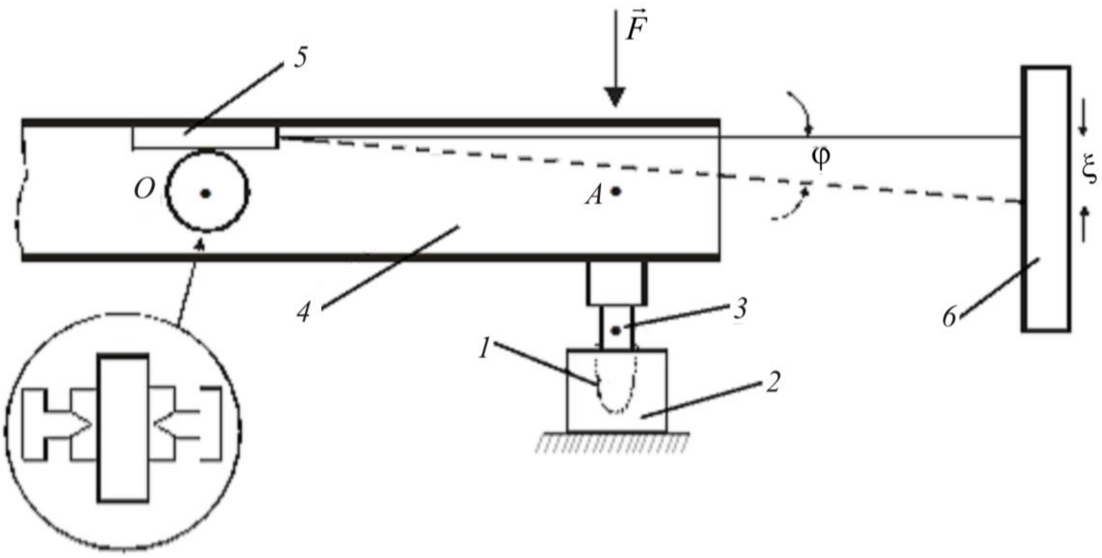

Fig. 1. The design of installation for quotients of longitudinal rigidity determination: *1* is implant; *2* is osseous tissue analog; *3* is pin; *4* is balancing lever; *5* is laser; *6* is screen

The angle φ of rotation of the lever *OA* and implant vertical movement Δ are determined according to formulae: $\varphi = \xi / L$, $\Delta = \varphi \cdot OA$, where L ($15 \le L \le 50$ m) is the distance from lever rotation center *O* to the screen ($\xi << L$). Loading was performed by small weights in such a way that the line of force passes along the implant axis (for tensile loads, a pulley was used). The technique of measurement is described in detail in paper [8].

To measure quotients of longitudinal stability, *Osstell ISQ* devices were used. They are handy, atraumatic, and may be applied once implants have been installed. But for quotients of lateral stability, the procedure of measurement when standard pins (*SmartPeg*) are used is such that every time for this purpose one must surgically open the mucoperiosteal flap, unscrew the plug closing a threaded hole in the implant (where the denture bearing part shall then be fastened), and install a magnetic pin which is an element of the device measuring system. Then, ISQ_n shall be measured and the mucoperiosteal flap shall be sutured again, i.e. tracking the osteointegration dynamics is possible but requires certain forces and time and is accompanied by noticeable loads on the osseous tissue that is not strong enough. Such an intervention may negatively impact on the osteointegration process.

But if a magnetic plug with the same magnet as in the magnetic pin (Fig. 2) will be used instead of a standard plug which closes the implant threaded hole in the course of osteointegration, such problems will not arise since ISQ_b may be measured through the mucous membrane of bone alveolus with no special preparation. Let us also note that a magnetic pin of such a large length is not necessary to excite longitudinal oscillations. The main advantage of a magnetic plug is considerable simplification of the measurement procedure and possibility to monitor the osteointegration process without mucoperiosteal flap opening.

Currently, the prosthetics technique with the use of mini dental implants is widely recognized around the world, including Russia. Detachable dentures are widely applied in treatment of the majority of aged patients with total absence of teeth. However, denture fixation and stabilization create certain difficulties that are mainly related to adverse clinical conditions of prosthetic beds, particularly in mandibles.

The use of mini dental implants as additional holding elements of detachable dentures may not make it possible to exclude specified disadvantages but, at least, allows their substantial leveling.

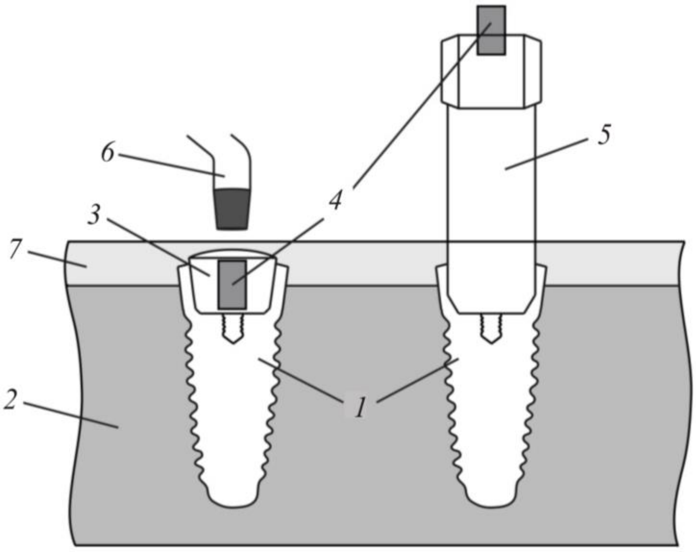

Fig. 2. ISQ_b measurement design when using a magnetic plug (*1* are dental implants; *2* is osseous tissue; *3* is magnetic plug with magnet *4*; *5* is *SmartPeg* pin; *6* is *Osstell ISQ* measuring probe; *7* is mucous membrane)

In comparison with classical screw implants, mini implants have a number of advantages: there are far less contraindications for their installation, requirements are lower to osseous tissue quality and geometry of the mandible alveolar crest due to a rather small diameter of implants, installation is made during a single visit with minimum surgical intervention. Implantation of mini implants is much cheaper than that of traditional dental implants [5, 11, 14].

Popularity and wide use of mini dental implants have naturally led to changes in their geometry and enhancement of their functional purpose [2–4]. Initially, they were only applied for improvement of fixation and stabilization of detachable dentures at total absence of teeth, and then, as mini dental implant dimensions increased, attempts appeared to use them as bearing elements at small vertical loads (absence of a single tooth).

After mini implants have been installed, the osteointegration process shall be monitored, and it shall be of high importance to watch dynamics of changes in their mobility in the first weeks after installation in order to correct them and regulate loads. We have suggested mini dental implant mobility assessment technique using the *Osstell ISQ* device that enables monitoring of the osteointegration process [1]. Its main point is as follows. A specially designed measuring cap with a magnetic element is fixed on the spherical head of mini dental implants with stomatological cement for temporary fastening of fixed orthopedic structures. It enables determination of quotients of stability under periodically applied longitudinal and lateral loads (Fig. 3).

Experiments showed that for dental implants fixed in osseous tissue analogs (Fig. 2), the values of quotients of longitudinal stability ISQ_b measured by the *Osstell mentor* device using a standard magnetic pin practically coincide with the appropriate values of coefficients of lateral stability ISQ_τ. Of 24 measurements, 11 times the ISQ_b/ISQ_τ ratio was exactly equal to 1; other 13 gave the difference of less than 7 %.

Moreover, for dental implants and mini dental implants fixed in osseous tissue analogs of polyurethane and linden, recent measurements by *Osstell ISQ* devices using magnetic plugs and magnetic caps showed even a higher level of coincidence for ISQ_b and ISQ_τ values: of 1000 measurements for dental implants and mini dental implants of various dimensions, 85 % gave an exact coincidence ($ISQ_b = ISQ_\tau$), and only 15 % gave difference of about 5 %. Thus, the quotient of longitudinal stability may be quite well used for assessment of implant

Fig. 3. Measurement design for quotients of longitudinal stability of mini dental implants using *Osstell ISQ* device: *1* is mini implant; *2* is measuring cap; *3* is temporary cement layer; *4* is magnetic element of the measuring cap; *5* is probe of the *Osstell ISQ* device; *6* is osseous tissue)

readiness for functional loads. We should notice here that unlike the ISQ_b/ISQ_τ ratio, the ISQ_n/ISQ_τ ratio (i.e. across and along a dentition) depends on alveolar crest dimensions and may be much less than 1.

MEASUREMENT OF QUOTIONS OF LONGITUDINAL STABILITY. MAGNETIC PLUG AND MAGNETIC CAP

Let us see experimental data showing possibility to use a magnetic plug for noninvasive monitoring of the osteointegration process. For this purpose, a series of experiments was conducted on implants with magnetic plugs. As an osseous tissue analog, solid-foamed material was used. Two options of magnet fastening in an implant were considered. The first option was for a cylindrical magnet of d = 2 mm, h = 4.3 mm from the magnetic pin of the *Osstell ISQ* device; it was fixed directly in the hole for the plug at the level with the upper edge using glue (like epoxide resin). In the second case, the lower part of a pin (*SmartPeg*) was cut off, and the rest was appropriately threaded so that after fastening a 2 mm part of the magnet would project over the implant surface to screw and unscrew the plug. Fig. 4 shows the observed ISQ_b data for such plugs. Depth of fastening l (implant screwing into the osseous tissue analog) changed in the course of the experiment, i.e. after a measurement for a certain l value, the implant was screwed more deeply, ISQ_b was measured for a new l value, and so on. Conmet implants of 4 mm in diameter and 15 and 19 mm in length were used. Since the observed ISQ_b data did not depend on implant dimensions and a method of magnet fastening (a kind of the magnetic plug), the diagram (Fig. 4) only shows S values of the area of implant and material contact. In a certain part of experiments, ISQ_b was measured through a 1–2 mm thick pigskin layer. These experimental points are marked as circles. Another part of experimental data represented as triangles meets measurements without covering (the solid line represents results of experimental data processing by the least square method).

The observed data show that the pigskin layer, as well as some other non-magnetic materials (organic glass, polyethylene, linoleum) does not influence instrument readings.

So, when having a magnetic plug, we can monitor ISQ_b without opening the mucous flap, i.e. without impact on the osteointegration process. This technique may be especially

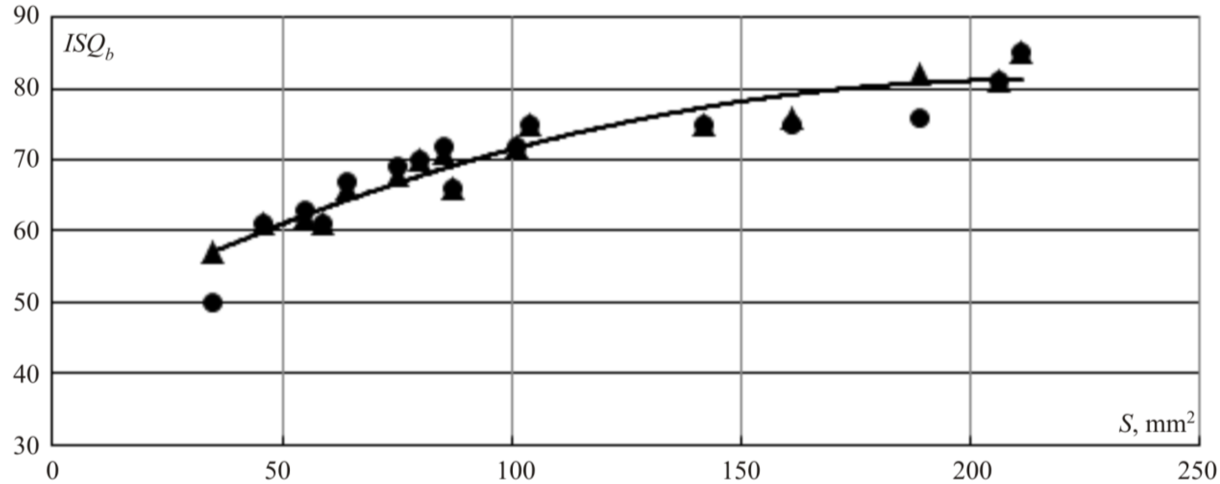

Fig. 4. Dependence of quotient of longitudinal stability on dental implant contact area with osseous tissue analog of solid-foamed material: ▲ is without covering; ● is with covering

useful when assessing results of various courses of intensive care where quick changes in strength of dental implant fastening are expected, as well as when determining terms of implant readiness for functional load.

One of the most important parameters of implants is the bearing capacity. Its assessment shall be a necessary and very important part of a pre-surgical analysis. There is no information on this matter in literature, and selection of a number and dimensions of mini dental implants shall be based on experience and intuition of an attending physician. There is a set of publications where criteria of implant readiness for functional loads are discussed. For example, when using the *Osstell ISQ* device, the majority of authors considers that an implant is ready for functional loads when the value of coefficient of stability $ISQ \geq 65$ [7, 12]. But, determination of values of these loads is not described. We shall only note some general reasons. If after dental implant installation, the coefficient of stability grows (or at least does not decrease) and makes $ISQ = 65$ (except for the first three weeks when its value may first decrease and then grow to initial level), then the situation may be considered satisfactory. If at the same time a patient's food ration is known (i.e. quantity and hardness of consumed products), we can assess the value of appropriate masticatory stresses and try to assess the bearing capacity of these dental implants by the technique stated in [13]. Not having such statistical data, let us compare the mini dental implant bearing capacity with that of classical screw implants assuming the former is a basis. For this purpose, we can provide the following criterion: *two implants with equal quotients of longitudinal rigidity* (*or stability*) *are equivalent,* i.e. they have equal bearing capacity in terms of mechanics.

Fig. 5 shows the dependence of the quotient of longitudinal rigidity K_b (MN/m) on S area (mm²) of implant contact with osseous tissue analog of polyurethane (1 are classical screw implants, 2 are mini implants). This dependence is close to linear.

Experiments show that quotients of longitudinal rigidity of big mini dental implants differ a little from similar values of K_b for classical implants with small dimensions and well fall into the general regularity. And as the latter are used in restorative operations as bearing elements of dentures, there is no reason to believe that mini implants cannot be used for the same purpose. Actually, for a long time orthopedic surgeons have to use mini dental implants as bearing elements in a number of special cases in restorative operations (when the esthetic function becomes more important than the masticatory one or on patients' urgent requests). In such cases, when selecting a number and dimensions of mini dental implants, scientifically based guidelines are desirable. The dependence shown in Fig. 5 can help to solve this question.

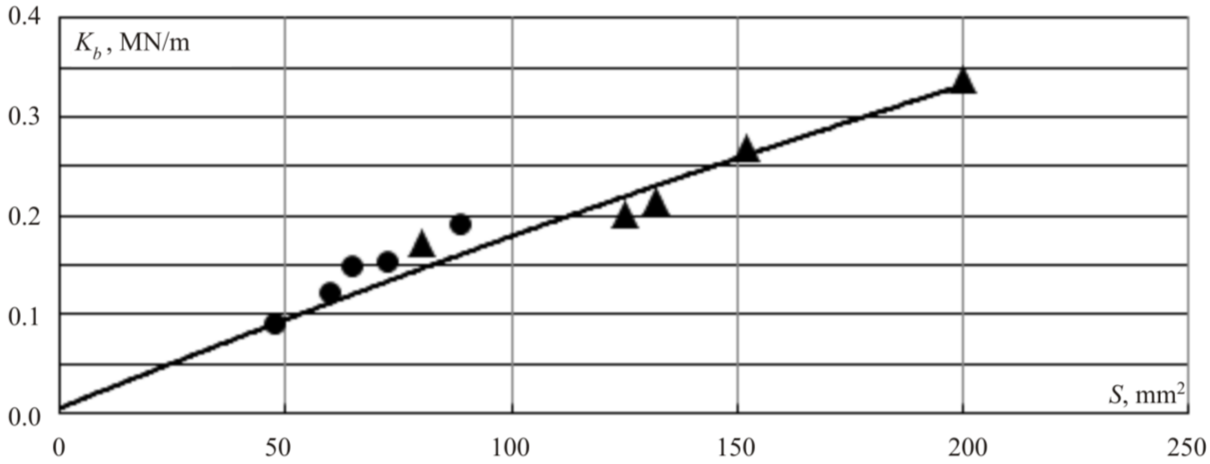

Fig. 5. Dependence of implant quotients of longitudinal rigidity K_b on S Area of implant contact with osseous tissue: ▲ are classical screw implants; ● are mini implants

Indeed, two mini dental implants may be installed instead of one classical dental implant, for example, if their bearing capacities are equivalent (i.e. if $k = k_1 + k_2$), and their installation is possible during a single visit with minimum surgical intervention and subsequent "immediate" loading. We should emphasize that although the experiments made on osseous tissue analogs do not give any idea of real values of coefficients of longitudinal rigidity, they make it possible to compare bearing capacities of implants of various dimensions and shapes.

COMPARISON OF QUOTIENTS OF LONGITUDINAL STABILITY AND LONGITUDINAL RIGIDITY

As we noted above, the strength of dental implant fastening in osseous tissue may be determined by two methods: measurement of quotients of stability (ISQ_b) using the *Osstell ISQ* device (resonance-frequency analysis) and determination of quotients of rigidity (K_b) by laser testing (static tests). Obviously, each dental implant fixed in any osseous tissue analog has two appropriate coefficients (ISQ_b and K_b) which characterize strength of implant fastening in that material. Experimental data on measurement of quotients of stability ISQ_b and rigidity K_b for dental implants of various shapes and dimensions fixed in different osseous tissue analogs obviously form a certain set $\{ISQ_b, K_b\}$. The question is – whether this set is a collection of random quantities or whether it reflects a certain physical regularity? Fig. 6 shows experimental data for all 10 investigated dental implants fixed in various osseous tissue analogs. Experimental data are shown in Tables 1, 2, and 3. Quotients of longitudinal rigidity K_b (MN/m) are on the horizontal axis (third line), quotients of longitudinal stability ISQ_b are on the fourth line.

The shown results demonstrate one-to-one correspondence between these values. The spread in experimental data is not apparently a consequence of only measurement errors. Quotients of stability do not obviously depend on only coefficients of rigidity but also on other parameters (medium density, Young's modulus, Poisson's ratio, osseous tissue viscosity, etc.).

To understand the physical meaning of the regularity shown in Fig. 6, let us build an oversimplified theoretical model of longitudinal oscillations for dental implants fixed in a viscous-elastic medium. Let m be the mass of a dental implant together with a magnetic plug (or a measuring cap with a magnet), x is its longitudinal displacement. In previous papers, when calculating the mode of deformation and assessing the resonance frequency value, Hooke's law correctness was supposed for the osseous tissue and its analogs [10]. Actually, we can only consider it as the first approximation when viscous (dissipative) forces which depend on the loading rate are small in comparison with elastic ones.

Table 1

Quotients of longitudinal rigidity and longitudinal stability (solid-foamed material)

Parameter	Number of sample									
	1	2	3	4	5	6	7	8	9	10
S, mm^2	79	85	120	123	124	148	150	200	200	210
K_b, MN/m	0.60	0.73	1.07	1.02	1.11	1.13	1.27	1.63	1.72	1.89
ISO_b	69	73	74	74	75	76	77	79	80	81

Table 2

Quotients of longitudinal rigidity and longitudinal stability (polyurethane, 1–5 are classical dental implants, 6–10 are mini dental implants)

Parameter	Number of sample									
	1	2	3	4	5	6	7	8	9	10
S, mm^2	78	119	126	143	190	47	58	64	105	106
K_b, MN/m	0.135	0.200	0.205	0.240	0.330	0.107	0.117	0.127	0.182	0.181
ISQ_b	25	32	32	37	41	35	35	35	40	35

Table 3

Quotients of longitudinal rigidity and longitudinal stability (1–5 are linden, classical dental implants, 6–10 are boxyl, classical dental implants)

Parameter	Number of sample									
	1	2	3	4	5	6	7	8	9	10
S, mm^2	85	125	132	150	200	84	118	143	186	189
K_b, MN/m	1.32	2.00	2.12	2.57	2.56	0.019	0.014	0.022	0.011	0.027
ISQ_b	77	83	83	85	81	2	3	5	1	7

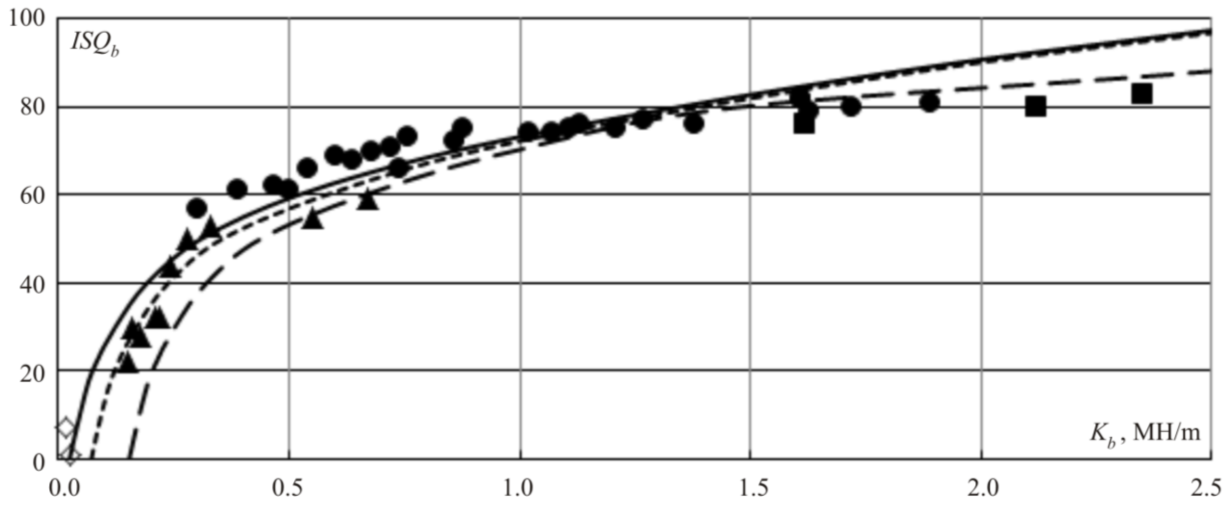

Fig. 6. Dependence of quotients of longitudinal stability ISQ_b on quotients of longitudinal rigidity K: ● is solid-foamed material; ▲ is polyurethane; ■ is linden; ◊ is boxyl

Now let us consider the Hooke's law modification proposed by Kelvin and Voigt, when the relation between Young's modulus E and relative deformation ε shall be as follows:

$$\sigma = E\varepsilon + \eta \frac{d\varepsilon}{dt},$$

where σ is stress, η is material viscosity, t is time [6].

The first term in the expression for σ is an elastic component of stress; the second one is its dissipative part.

For a dental implant fixed in such an osseous tissue analog, the equation for longitudinal forced oscillations shall be as follows:

$$m\ddot{x} = -k_b x - \mu\dot{x} + Q_0 \sin pt$$

or

$$\ddot{x} + 2b\dot{x} + k^2 x = P_0 \sin pt,$$

where $2b = \mu/m$, $k^2 = k_b/m$, $P_0 = Q_0/m$ (μ is material viscosity, m is dental implant mass, Q_0 and p is amplitude and frequency of the disturbing (driving) force, accordingly). As is well known, in this case amplitude A of forced oscillations shall be as follows [15]:

$$A = \frac{P_0}{\sqrt{(k^2 - p^2)^2 + 4b^2 p^2}}.$$

It can be easily shown that if $p = \sqrt{k^2 - 2b^2}$, the forced oscillation amplitude shall have the maximum. When $k^2 \le 2b^2$, the osseous tissue viscosity shall exceed the critical value and vibration amplitude A shall monotonically decrease through the entire range of parameter p change.

Now let us determine coefficients of viscosity for osseous tissue analogs. Natural frequency of elastic oscillations for a "dental implant + magnetic plug" system fixed in an osseous tissue analog shall be $k = \sqrt{k_b/m}$. Resonance frequency of a "dental implant + magnetic plug" system fixed in a viscous-elastic medium shall be $p = 2\pi f(ISQ)$ according to ISQ_b data observed with the use of the *Osstell ISQ* device.

The dependence between resonance frequency f of the driving force and coefficient of stability ISQ for "dental implant + SmartPeg" shall be as follows:

$$ISO = -2.4 \cdot 10^{-14} \cdot f^4 + 7.1 \cdot 10^{-10} \cdot f^3 - 7.8 \cdot 10^{-6} \cdot f^2 - 4.45 \cdot 10^{-2} \cdot f - 37,$$

refer also to Table 4; these data have been submitted by the *Osstell AB* senior management.

Thus, the quotient of medium viscosity may be determined by formula $b = 0.707\sqrt{k^2 - p^2}$. The obtained values of b parameters determined for solid-foamed material, polyurethane, and linden when processing experimental data shall be as follows: $b_1 = (9.2 \pm 3.5)\ 10^3\ s^{-1}$ (solid-foamed material), $b_2 = (9.4 \pm 2.1)\ 10^3\ s^{-1}$ (polyurethane), and $b_3 = (19.2 \pm 2.3)\ 10^3\ s^{-1}$ (linden). For these materials, quotients of rigidity K_b and stability ISQ_b used in calculation are shown in Tables 1, 2, and 3. Knowing values of b parameters for these materials, we obtain the following average values of their coefficients of viscosity: for solid-foamed material, μ = (11.9 ± 4.5) N/(m/s); for polyurethane, μ = (12.1 ± 2.7) N/(m/s); for linden, μ = (24.8 ± 3.0) N/(m/s).

We failed to determine the value of b parameter and, therefore, quotient of viscosity μ for boxyl because of wide spread of experimental data, though its value of quotient of viscosity is obviously small (μ ≈ 1 N/(m/s)).

Table 4

Dependence of quotient of stability *ISQ* on resonance frequency *f*

Parameter	*ISQ*										
	0	10	20	30	40	50	60	70	80	90	99
f, Hz	977	1343	1709	2197	2747	3479	4517	5737	7263	8728	10132

Table 5

Quotients of stability and quotients of rigidity for dental implants installed in osseous tissue analogs (calculation)

K_b, MN/m	ISQ_b										
	0	10	20	30	40	50	60	70	80	90	99
$b = 0$	0.024	0.046	0.073	0.123	0.192	0.308	0.519	0.855	1.340	1.940	2.610
$b = 6{\cdot}10^3$ s^{-1}	0.071	0.092	0.121	0.169	0.238	0.354	0.579	0.901	1.388	1.980	2.660
$b = 10^4$ s^{-1}	0.153	0.175	0.203	0.252	0.321	0.437	0.662	0.984	1.471	2.660	2.740

Research for determination of coefficients of viscosity μ given above shall be treated as methodological, and values of b and μ parameters – as approximate (estimated).

Using such an approach, we might determine viscosity for an osseous tissue where implants fasten. But unfortunately, there is no information on coefficients of stability ISQ_b and rigidity K_b for dental implants fixed in the osseous tissue. Let us try to estimate reliability of the above theoretical model. Let us assume that b parameters of osseous tissue analogs where dental implants fasten are certain constants. If the theoretical model is correct, the design curves obtained by formulae for the viscous-elastic medium shall satisfactorily match experimental data.

The algorithm of calculation for these dependences shall be as follows:

- b parameter and the value of quotient of longitudinal stability ISQ_b shall be set.
- Resonance frequency f that meets ISQ_b shall be determined (refer to Table 4 or formula $ISQ = ISQ(f)$).
- The value of circular frequency $p = 2\pi f$ shall be calculated.
- The value of quotient of longitudinal rigidity shall be determined by formula: $K_b = k^2 m$, where $k^2 = p^2 + 2b^2$, m is mass of “dental implant + magnetic cap”.

For example:

$b = 10^4$ s^{-1}, $ISQ = 60$, $f = 4517$ s^{-1}, $p = 2\pi f = 28.37{\cdot}10^3$ s^{-1},

$m = 0.52 + 0.125 = 0.645$ $g = 0.645{\cdot}10^{-3}$ kg (dental implant No. 4 + magnetic plug);

$b = 10.0{\cdot}10^3$ s^{-1};

$K_b = k^2 m = (p^2 + 2b^2)\, m = (28.37^2 + 200)\, 10^6{\cdot}0.645{\cdot}10^{-3} = 0.648{\cdot}10^6$ N/m.

In Fig. 6 above, the solid, dashed, and dash-and-dot lines are the design curves obtained by the proposed algorithm of calculation for “dental implant No. 4 + magnetic plug” installed in a viscous-elastic medium, when the values of b parameters are as follows: $b_1 = 0$, $b_2 = 6.0{\cdot}10^3$ s^{-1}, $b_3 = 10^4$ s^{-1}, accordingly (Table 5).

The comparison shows that design curves for elastic ($b = 0$) and two viscous-elastic ($b = 6{\cdot}10^3$ s^{-1} and $b = 10{\cdot}10^3$ s^{-1}) media give good qualitative and quite good quantitative compliance with the experimental data obtained with the use of osseous tissue analogs. For $50 < ISQ_b < 85$, the difference makes 8–12 %. For $0 < ISQ_b < 50$, the viscosity influence becomes significant, especially for small ISQ_b values, therefore viscosity of various types of osseous tissue shall be assessed in the future. However, it shall mainly be assessed for mini implants and classical dental implants of small dimensions, since middle and big classical implants are usually subject to removal at such values of ISQ_b.

CONCLUSIONS

The obtained results confirm adequacy of the *Osstell ISQ* device and expediency to use quotients of longitudinal stability for assessment of dental implants readiness for functional loads. The use of magnetic plugs and magnetic caps will enable considerable enhancement of capabilities for noninvasive control of osteointegration level and efficiency of reconstructive surgery and orthopedics.

The conducted research confirms that the osseous tissue of upper and lower jaws may be considered as a viscous-elastic medium and enables determination of osseous tissue viscosity.

REFERENCES

1. Arutyunov S.D., Yeroshin V.A., Stepanov A.G., Boyko A.V., Daov A.N., Matsaberidze L.G. Novye tendentsii ispolzovaniya dentalnykh mini-implantatov [New tendentions in use of mini dental implants]. *Rossiyskiy vestnik dentalnoy implantologii*, 2013, no. 2, pp. 14-20 (*in Russian*).
2. Balkin B.E., Steflik D.E., Naval F. Mini-dental implant insertion with the auto-advance technique for ongoing applications. *Journal of Oral Implantology*, 2001, vol. 27, pp. 32-37.
3. Bulard R.A. Mini dental implants: enhancing patient satisfaction and practice income. *Dent. Today*, 2001, vol. 20, pp. 1-5.
4. Christensen G.J. The “mini implant” has arrived. *Journal of American Dental Association*, 2006, vol. 137, pp. 387-390.
5. Christensen G.J. Implants and the general practitioner. *JADA*, 2000, vol. 131, pp. 359-361.
6. Davies R.M. *Volny napryazheniy v tverdykh telakh* [Stress waves in solids]. Moscow: Inostrannaya literatura publishers, 1961, 103 p. (*in Russian*).
7. Drobyshev A.Yu., Dronov M.V. Otsenka stabilnosti I osteointegratsii dentalnykh implantatov s primeneniem rezonansno-chastotnykh implantatov s primeneniem rezonansno-chastotnogo metoda [Assessment of dental implant stability and osteointegration with the use of resonance frequency method]. *Institut stomatologii*, 2007, no. 1, pp. 128-129; 2007, no. 3, pp. 64-65 (*in Russian*).
8. Eroshin V.A., Arutyunov S.D, Arutyunov A.S., Unanyan V.Ye., Boyko A.V. Mobility of dental implants: devices and diagnostic methods. *Russian Journal of Biomechanics*, 2009, vol. 12, no. 2, pp. 23-36.
9. Eroshin V.A., Dzhalalova M.V., Boyko A.V., Arutyunov S.D., Stepanov A.G., Daov A.N. Mobility of dental implants: new capability of a known device. *Russian Journal of Biomechanics*, 2015, vol. 19, no. 3, pp. 236-243.
10. Eroshin V.A., Dzhalalova M.V. Stress-strain state of biomechanical system implant-elastic foundation. *Russian Journal of Biomechanics*, 2012, vol. 16, no. 3, pp. 70-81.
11. Flanagan D., Mascolo A. The mini dental implant in fixed and removable prosthetics: a review. *Journal of Oral Implantology*, 2011, vol. 37, pp. 123-132.
12. Markin V.A., Olesova V.N., Arutyunov S.D., Mushaev I.Ch., Pozdnyaev A.I., Tarafutdinov D.M. Chastotno-resonansnoie testirovanie vnutrikostnykh implantatov na nizhney chelusti kak metod obsledovaniya ikh neposredstvennoy nagruzki [Frequency resonance testing of ventplants in mandibles as an inspection method for their direct load]. *Rossiyskiy stomatologicheskiy zhurnal*, 2006, no. 1, pp. 44-46 (*in Russian*).
13. Perevezentseva A.A. *Vrachebnaya taktika vybora konstruktsionnogo materiala vremennykh protezov* [Medical tactics of constructional material selection for temporary dentures]. Ph.D. Thesis. Moscow, 2012, 134 p. (*in Russian*).
14. Shatkin T.E., Shatkin S., Oppenheimer B.D., Oppenheimer A.J. Mini dental implants for long term fixed and removable prosthetics: a retrospective analysis of 2514 implants placed over a five year period. *Compendium*, 2007, vol. 28, pp. 36-41.
15. Targ S.M. *Kratkiy kurs teoreticheskoy mekhaniki* [Short course in theoretical mechanics]. Moscow: Nauka, 1968, 479 p. (*in Russian*).

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