Dynamics of the Periotest method of diagnosing the dental implant–bone interface

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The physical basis of the Periotest method has been investigated on the basis of lumped parameter system models. Theoretical values of the force to which an implant is subjected by tapping have been favourably compared with experimental results from the literature.

1. Introduction

At the present stage of biomaterials science there is no dental implant material which is widely recognized to induce a sound periodontal ligament-like interface [1, 2]. A variety of mineralized interface-inducing biomaterials are instead being used or tested [1–4]. Studies [2, 4] suggest that stable interfacial mineralization over an ample area takes a fairly long healing time after implantation. Premature loading of any dental implant is liable to induce some unfavourable fibrous tissue at the interfacial region [2]. Diagnosis of the interfacial mineralization state is therefore imperative. Medical radiography is useful but unsatisfactory, because its optimal resolution capacity is about 100 μm [5].

Several years ago a portable instrument to assess the mobility of a tooth or dental implant by tapping was commercialized under the name Periotest [6, 7]. The instrument is widely applied to clinical and experimental diagnoses of various implants: for alumina [8–12], for apatite [8, 9, 13–17], for titanium [8, 9, 12, 18–22] and for bioactive glass-ceramic [23].

The Periotest method is based on the empirical fact that teeth having smaller mobility tend to have shorter durations of contact with a tapping rod [24, 25]. The contact time τ is measured as follows [25, 26]. First, a metal rod hits the specimen at a constant speed (10–30 $\mathrm{cm\,s^{-1}}$) and generates an acceleration signal which is detected by a small accelerometer at the end of the rod. Then, τ is estimated from that signal. The mobility is expressed as an integer (-8 to $+50$) called the Periotest value (PTV), to which τ is related by the formulae [25]

$$\tau = 0.020(PTV + 21.3)\ [\mathrm{ms}] \quad PTV \leqq 13 \quad \text{(1a)}$$

$$\tau = 0.0006(PTV + 4.17)^2 + 0.50958\ [\mathrm{ms}] \quad PTV > 13 \quad \text{(1b)}$$

Most of the clinical data hitherto published show that PTV for implants is lower than 13.

It is of interest to estimate the force F delivered to the implant by the Periotest diagnosis and its displacement x; such estimation will be useful, particularly for the application to the diagnosis of an implant at an early healing period. Kaneko [27] showed that the peak value of F was about 20 N for a modelled system (PTV: -4) consisting of a phenolic resin rod (implant), 0.2 mm thick paper tape (interface) and a metal base (bone). Teerlinck *et al.* [22] estimated the value to be 18–12 N for PTV -4 to $+2$ as a preliminary experimental result. In this paper theoretical expressions of F and x are derived as functions of τ and their values are estimated.

2. Dynamics of the Periotest diagnosis

We express the Periotest diagnosis by a lumped parameter system model as shown in Fig. 1, based on three assumptions. First, the effective compliance c is the only unknown parameter to be determined from the contact time τ, because this is the only quantity measured. The effect of viscous damping will be discussed in section 3. Second, the tapping rod and the implant are rigid particles. We should therefore note that c will depend on the tap point and direction of a real implant. In fact, such dependence of the Periotest value

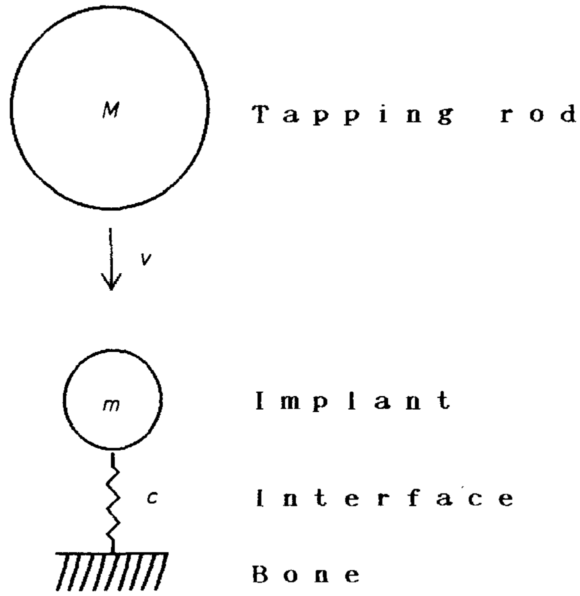

Figure 1 A lumped parameter system model of the Periotest diagnosis. Viscous damping is disregarded. M: mass of the tapping rod, v: velocity of the tapping rod, m: mass of the implant, c: effective compliance of the interface.

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(PTV) is well known [7, 14]. Lastly, the mass m is the sum of the mass of the implant and the effective mass of the cortical bone surrounding it, or the mass of the implant alone, depending on whether the interface is hard or soft. Therefore, c represents the effective compliance of the bone supporting the implant or that of the interface.

The energy balance is

$$(1/2)Mv^2 = [1/(2c)]x^2 + (1/2)(M+m) \times (\mathrm{d}x/\mathrm{d}t)^2 \quad 0 \leqq t \leqq \tau \tag{2}$$

Here x is the displacement of the implant taken positive in the v direction and t is the time after impact starts. Therefore, taking into account that $-\mathrm{d}x/\mathrm{d}t$ has a maximum at $t = \tau$, we have

$$x = 0 \qquad \text{at } t = \tau \tag{3}$$

From Equations 2 and 3 we obtain

$$c = \pi^{-2}(M+m)^{-1}\tau^2 \tag{4}$$

$$x = x_0 \sin \omega t \qquad 0 \leqq t \leqq \tau \tag{5}$$

taking into account that $x = 0$ at $t = 0$, where

$$x_0 = (Mc)^{1/2} v \tag{6a}$$

$$= \pi^{-1}[M/(M+m)]^{1/2} v\tau \tag{6b}$$

$$\omega = \pi/\tau \tag{7}$$

Equation 4 is the expression giving the relationship between c and τ. Equation 6b confirms the empirical fact [24, 25] that a shorter duration of impact on a specimen corresponds to a smaller displacement. From Equations 1a and 6b we have

$$x_0 = 0.2\pi^{-1}[M/(M+m)]^{1/2} \times v(PTV + 21.3) \quad [\mu\mathrm{m}] \quad PTV \leqq 13 \tag{8}$$

where v is expressed in cm s^{-1}. Equation 8 is the expression giving the relationship between the maximum displacement of the implant and PTV. From Equations 1a and 4 we have

$$c^{-1} = 25\pi^2(M+m)(PTV+21.3)^{-2} \quad [10^5\,\mathrm{N/m}] \quad PTV \leqq 13 \tag{9}$$

where M and m are expressed in g. Equations 4 and 9 imply that τ and PTV depend on the mass of the specimen too. From Equations 8 and 9 we get

$$\Delta x_0/x_0 \fallingdotseq \Delta PTV/(PTV+21.3) \quad \text{and} \quad \Delta c/c \fallingdotseq 2\Delta PTV/(PTV+21.3) \tag{10}$$

for $PTV \leqq 13$. If we let $\Delta PTV = \pm 1$, which is the minimal ΔPTV measured, then

$$|\Delta x_0/x_0| \fallingdotseq (PTV+21.3)^{-1} \quad \text{and} \quad |\Delta c/c| \fallingdotseq 2(PTV+21.3)^{-1} \tag{11}$$

for $PTV \leqq 13$. These equations determine the resolution capacities of x_0 and c estimated from the Periotest diagnosis; the former is 8–3% for PTV -8 to $+13$.

The compressive force F in the interface is given by

$$F = x/c \tag{12}$$

From Equations 1a, 4 and 5 we have

$$F = F_0 \sin \omega t \qquad 0 \leqq t \leqq \tau \tag{13}$$

$$\int_0^\tau F\,\mathrm{d}t = 2[M(M+m)]^{1/2} v \tag{14}$$

Here

$$F_0 = (M/c)^{1/2} v \tag{15a}$$

$$= \pi[M(M+m)]^{1/2} v\tau^{-1} \tag{15b}$$

$$= 0.5\pi[M(M+m)]^{1/2} v/(PTV+21.3) \quad [\mathrm{N}] \quad PTV \leqq 13 \tag{15c}$$

where M and m are expressed in g and v in cm s^{-1} unit. Equation 15b shows that a shorter impact duration generates a larger impact force.

On the basis of the data from the literature [7, 25], we assume

$$M = 8.4\,[\mathrm{g}] \quad \text{and } v = 20\,[\mathrm{cm\,s^{-1}}] \tag{16}$$

We assume the mass of a dental root implant to be 0.4 g according to [27] and the effective mass of the cortical bone surrounding it to be 2.4 g according to [28]. Then

$$m = 0.4 \text{ or } 2.8\,\mathrm{g} \tag{17}$$

dependent on whether the implant–bone interface is soft or hard. From Equations 8, 9 and 15c we have

$$15 \leqq x_0 \leqq 43 \quad [\mu\mathrm{m}] \tag{18}$$

$$1.8 \leqq c^{-1} \leqq 16 \quad [10^5\,\mathrm{N\,m^{-1}}] \tag{19}$$

$$7.9 \leqq F_0 \leqq 23 \quad [\mathrm{N}] \tag{20}$$

for $-8 \leqq PTV \leqq 13$. Equations 11 and 18 suggest that the Periotest diagnosis has a resolution capacity superior to that of medical radiography (about 100 μm). From Equation 15c we have

$$F_0 = 16 \text{ and } 12\,\mathrm{N} \quad \text{if } m = 0.4\,\mathrm{g} \quad \text{(soft interface)} \tag{21a}$$

$$= 18 \text{ and } 13\,\mathrm{N} \quad \text{if } m = 2.8\,\mathrm{g} \quad \text{(hard interface)} \tag{21b}$$

for PTV of -4 and $+2$, respectively, which are in good agreement with the experimental values (18 and 12 N) reported by Teerlinck *et al.* [22]. From Equation 9 we have

$$c^{-1} = 3.1 \times 10^5\,\mathrm{N\,m^{-1}} \quad \text{if } m = 0.4\,\mathrm{g} \quad \text{(soft interface)} \tag{22a}$$

$$= 4.0 \times 10^5\,\mathrm{N\,m^{-1}} \quad \text{if } m = 2.8\,\mathrm{g} \quad \text{(hard interface)} \tag{22b}$$

for $PTV = +5$. Equation 22a is in reasonable agreement with the value (2×10^5 N m^{-1}) which Saratani *et al.* [11] estimated by analysing the mobility spectrum obtained from random noise tapping on an alumina implant of $PTV = +5$.

3. Effect of viscous damping

In this Section we examine the effect of viscous damping on the force F, the displacement x and the contact time τ to which the implant is subjected by tapping. We express the Periotest diagnosis by a second lumped parameter system model as shown in Fig. 2.

The energy balance is given by

$$(1/2)Mv^2 = [1/(2c)]x^2 + (1/2)(M+m)(\mathrm{d}x/\mathrm{d}t)^2 + \eta \int_0^t (\mathrm{d}x/\mathrm{d}t)^2\,\mathrm{d}t \tag{23}$$

for $0 \leqq t \leqq \tau$. From the above equation we have, after a lengthy calculation

$$\tau = \pi\omega^{-1}(1 - \pi^{-1}\phi) \tag{24}$$

$$x = x_0 \exp(\lambda t)\sin\omega t \qquad 0 \leqq t \leqq \tau \tag{25}$$

$$F = F_0 \exp(\lambda t)\sin(\omega t + \phi) \quad 0 \leqq t \leqq \tau \tag{26}$$

$$\int_0^\tau F\,\mathrm{d}t = [M(M+m)]^{1/2}\{\exp[\lambda\omega^{-1}(\pi - \phi)] + 1\}v \tag{27}$$

Here

$$\Lambda = c\eta^2/(M+m) \tag{28}$$

$$\omega = [(M+m)c]^{-1}(1 - 0.25\Lambda)^{1/2} \tag{29}$$

$$\phi = \sin^{-1} c\eta\omega \tag{30}$$

$$x_0 = (Mc)^{1/2}(1 - 0.25\Lambda)^{-1/2}v \tag{31}$$

$$\lambda = -0.5(M+m)^{-1}\eta \tag{32}$$

$$F_0 = (M/c)^{1/2}(1 - 0.25\Lambda)^{-1/2}v \tag{33}$$

From the above equations the maximum displacement x_{max} and the maximum impact force F_{max} can be derived:

$$x_{max} = (Mc)^{1/2} v \exp(\lambda T_1) \tag{34}$$

$$F_{max} = (M/c)^{1/2} v \exp(\lambda T_2) \tag{35}$$

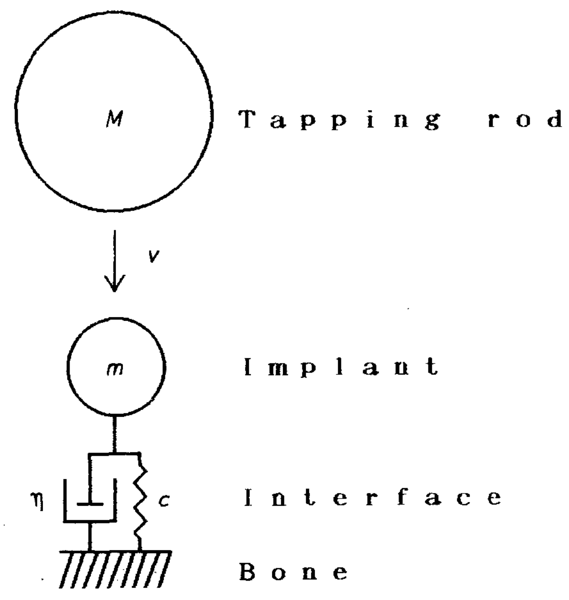

Figure 2 A lumped parameter system model of the Periotest diagnosis. η: viscosity of the interface. M, etc. as in Fig. 1.

with

$$T_1 = 0.5\pi\omega^{-1}(1 - 2\pi^{-1}\theta) \tag{36}$$

$$T_2 = 0.5\pi\omega^{-1}(1 - 2\pi^{-1}\psi) \tag{37}$$

Here

$$\theta = \cos^{-1}\{\omega[(M+m)c]^{1/2}\} \tag{38}$$

$$\psi = \cos^{-1}\{\omega[(M+m)c]^{1/2}(1 - \Lambda)\} \tag{39}$$

When η is small, we get

$$\tau \fallingdotseq \pi[(M+m)c]^{1/2}(1 - \pi^{-1}\Lambda^{1/2}) \tag{40}$$

$$x_{max} \fallingdotseq (Mc)^{1/2}(1 - 0.25\pi\Lambda^{1/2})v \tag{41a}$$

$$\fallingdotseq \pi^{-1}[M/(M+m)]^{1/2}v \times [1 - (0.25\pi - \pi^{-1})\Lambda^{1/2}]\tau \tag{41b}$$

$$F_{max} \fallingdotseq (M/c)^{1/2}(1 - 0.25\pi\Lambda^{1/2})v \tag{42a}$$

$$\fallingdotseq \pi[M(M+m)]^{1/2}[1 - (0.25\pi + \pi^{-1})\Lambda^{1/2}]v\tau^{-1} \tag{42b}$$

$$\int_0^\tau F\,\mathrm{d}t \fallingdotseq 2[M(M+m)]^{1/2}(1 - 0.25\pi\Lambda^{1/2})v \tag{43}$$

Equations 40 to 42 show that viscous damping as shown in Fig. 2 reduces τ as well as x_{max} and F_{max}. Equation 43 implies that the effect of viscous damping can be detected by measuring the force–time history of impact.

4. Summary

Theoretical expressions of the force and displacement to which an implant is subjected in the Periotest diagnosis have been derived on the basis of lumped parameter system models. It has been shown that the theoretical force obtained can be favourably compared with experimental results.

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