Norbert Enkling

Osseoperception: tactile sensibility of dental implants?

Teeth as sensory instruments

"Teeth as sensory instruments" was the title given by Münch and Schriever as early as 1931 in keeping with the tradition of Peaslee (1857) and Sigmund (1867), who were already aware of the fine tactile sensibility of teeth (quoted from Utz, 1982 [65]). The complex stomatognathic system has a built-in protective reflex that produces an unpleasant sensation when biting on a hard object; which leads to reflexive mouth opening and thus reduces damaging influences on the system [76]. Besides the functions that teeth fulfill during speech, food intake and food processing, they also play an esthetic role and are involved in the neural reflex control circuit of the stomatognathic system: teeth serve to sense foreign bodies and to ensure the jaw posture [65].

The types of spatial perception via the teeth have been investigated in several studies [75]:

- the perception of interocclusal test objects = active tactile sensibility
- the perception of axial and/or horizontal contacts of the teeth = passive tactile sensibility = sensation of pressure
- the ability to discriminate interocclusal thicknesses = discrimination ability
- the ability to recognize shapes in the oral cavity or to distinguish between two points of contact (stereognosis).

Jacobs emphasized that passive tactile sensibility can only perceive stimuli from single neural receptors, whereas active tactile sensibility represents normal function and involves all types of receptors such as muscle, joint, or tegument receptors [23].

Therefore, when examining the sensibility of the tooth as part of a control mechanism, it makes sense to use active tactile sensibility.

The active tactile sensibility of natural teeth varies greatly between individuals: in the study performed by Utz, natural teeth had a median tactile sensibility of approximately 15–30 µm, with the exception of canine teeth, which had a tactile sensitivity of 60 µm. However, the interindividual values varied between 2 µm and 425 µm [65, 66]. In more recent studies, the absolute values of tactile sensibility of natural teeth varied between 2 µm and 77 µm with a mean value of 17 µm for different individuals [14]. The influence of gender on tactile sensibility is small at best [61]: Most authors could not determine any correlation [4, 14, 65]. However, there appears to be a correlation between tactile sensibility and age: with increasing age, tactile sensibility decreases [18]. The mean increase in the interocclusal tactile threshold is circa 2.2 µm for every ten years of age. Moreover, subjects with increased individual tactile sensibility threshold values show greater tactile sensation uncertainty [14].

Osseoperception

Studies on osseointegrated orthopedic prostheses after the amputation of arms or legs have shown that such treatments resulted in a return of sensation due to mechanical stimulation [10, 34]. This recovery of somatosensory control circuits permits a more natural use of dentures and reduces the risk of denture and implant overloading [24]. Patients were able to discriminate between different mechanical stimuli acting on the osseointegrated prostheses [10, 56]. This ability was greater by 27 % compared to patients with conventional tubular prostheses [24]. An activation of receptors in the bone, periosteum, joint capsule or other tissues is assumed to be the cause of the stronger sensitivity [29].

Today, missing teeth can be replaced with alloplastic implants with a high probability of survival. Such restorations come close to a "restitutio ad integrum" [38]. However, the question regarding the extent to which dental implants are integrated into the existing stomatognathic control circuit remains unanswered [2]: does the "implant as a foreign body" need to be protected in a special way [31], or can it be considered a "fully fledged replacement tooth" with its own sensory perception [60]? Early on, Mühlbradt et al. discovered that sensory information can also be transmitted by dental implants [45, 46]. The ability of allo-

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plastic, and thus, non-vital, ankylotic-anchored titanium implants to develop some degree of tactile sensibility has been the subject of numerous publications in the past two decades. Brånemark coined the term “osseoperception” for them [5, 6, 41].

Physiology of dental sensory perception

Proprioceptors and exteroceptors are responsible for the tactile sensibility of teeth: proprioceptors, such as muscle spindles and joint receptors, are activated by stimuli from within the body and provide information about the relative position and movement of the body’s parts. They are distinguished from exteroceptors, which are stimulated by external stimuli and are located in the skin, mucosa, periosteum, bone, gingiva, and periodontal ligament. Exteroceptors provide information to the central nervous system about external loads and play an important role in tactile sensibility [23].

Depending on mouth opening, both proprioceptors and exteroceptors play a role in the interocclusal tactile sensibility of natural teeth: during wide mouth opening, interocclusal tactile sensibility can be attributed primarily to the muscle spindles and joint receptors of the temporomandibular joint [8, 9, 33].

With less interocclusal distance, i.e. with smaller thicknesses of the interposed foreign bodies, the tactile sensitivity becomes finer and is determined by the exteroceptors [26, 71]. These mechanoreceptors are located in the gingiva, the alveolar mucosa, and above all in the periodontal ligament, which in turn already reacts to low forces applied on the teeth. Van Steenberghe found that the functional properties of periodontal receptors are comparable to those of receptors found in the rest of the body skin [71]. Subsequently, the assumption that nerve endings of the dental pulp might be involved in tactile sensibility in addition to nociception could not be corroborated [35]. Endodontically treated teeth exhibit the same tactile sensibility as vital teeth [65].

The recorded EMG reflex responses are reduced by approx. 90 % under local anaesthesia of the examined tooth [69]. This led to the conclusion that the periodontal mechanoreceptors have a dominant function; the joint and muscle receptors therefore only play a subordinate role [43, 72]. However, the finding that a compromised periodontium following periodontitis does not lead to a reduction in tactile sensibility brings into question the dominant role of the periodontium [39]. The neurophysiological receptor apparatus, which is activated when a tooth undergoes intrusion in its alveolar socket as a result of occlusal load, is absent for implants (Figs. 1 and 2).

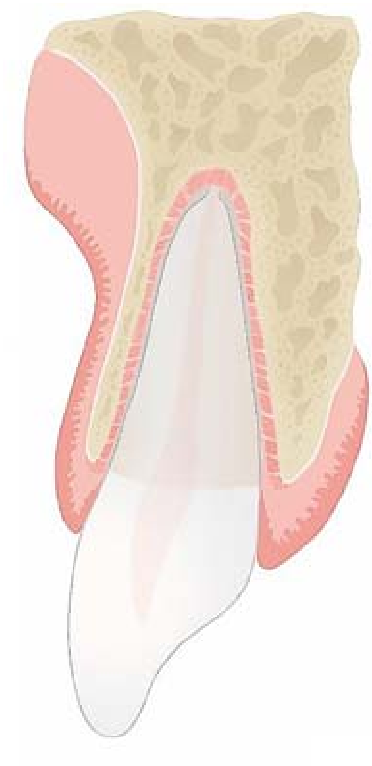

Figure 1 Schematic representation of a cross-section through a natural tooth together with periodontal tissue.

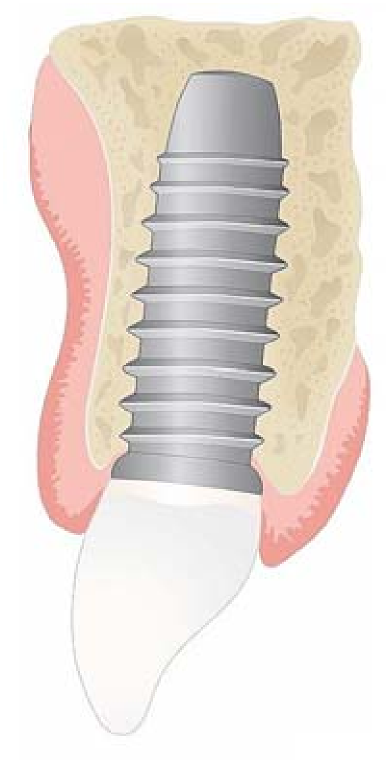

Figure 2 Schematic representation of a cross-section through an osseointegrated implant together with peri-implant hard and soft tissue.

The physiological mobility of teeth differs from that of implants. Tooth movement can be divided into two phases: in the first phase, under minor loading of the tooth, tooth mobility is determined and/or constrained by the fibers of the desmodont. In the second phase of movement, with increased loading, the bone undergoes elastic deformation as soon as the capacity of the desmodont is exhausted [32, 48, 60]. The mobility of an osseointegrated implant is entirely attributable to the elastic deformation of the bone under both horizontal and axial loading, and it can reach only one tenth of the mobility of natural teeth [52, 59]. However, Richter reconstructed a different behavior of natural teeth: the hydraulic system of the periodontium is only subjected to very short-term forces under physiological loads, e.g. during speech and chewing; tissue fluid cannot be displaced from the periodontal gap because this would require forces acting for a longer period of time. So, with normal function, natural teeth behave very similarly to implants in their movement pattern. The large intrusion capacity of the teeth is only exhausted in the case of parafunctions [54].

Methods to examine tactile sensibility

In principle, there are two different approaches to determine the stimulus threshold values of receptors [23]:

Figure 3a Experimental procedure for interocclusal tactile sensibility/active tactile sensibility: cheek retractors are used to retract the corners of the mouth and a test foil is inserted in the interocclusal space.

Figure 3b Test position: after the investigator's request, teeth clenching is performed by the subject.

1. the neurophysiological examination method and
2. the psychophysical examination method

In the neurophysiological examination method, an objective evaluation of the stimulus response of the receptors can be carried out invasively via microelectrodes and non-invasively via a recording of somatosensory evoked potentials. Alternatively, functional magnetic resonance imaging (fMRI) can be used to record changes in the brain when the tooth/implant is stimulated [36].

In the psychophysical examination method, the acting stimulus is compared to the subjective sensation of the test subject. If carefully applied in a standardised experimental setup, the psychophysical methodology can be used to establish a correlation between physiological functions of receptors and subjective responses of subjects in the context of an investigation of receptor sensitivity threshold, and it provides equally valid results compared to the more invasive, neurophysiological investigation methods. The psychophysical method can also be applied to larger sample populations than the neurophysiological method, and thus, it leads to more valid statements [68].

In the active tactile sensibility test, subjects are asked to bite on interocclusal foreign bodies of varying thickness. So-called "blank trials" (mock trials) are included in the test in order to check the statements of subjects (Figs. 3a, 3b). The test can thus come to the following results:

true positive =	presence of a foreign body was correctly detected by the subject
true negative =	absence of a foreign body was correctly detected
false positive =	despite the absence of a foreign body, one was reported as being present
false negative =	a presence of a foreign body was not detected

The 50 % value (proportion of correct answers = 50 %) has become established as the definition of tactile sensibility [64]. Since this 50 % value can be achieved with several foreign body thicknesses, the interpolated 50 % value is specified [26] (cf. Fig. 4). Recent literature recommends an evaluation by means of a logistic regression or – even more precisely – using an asymmetric Weibull distribution as an approximation to the tactile sensibility curve. This model has the advantage that, in addition to the 50 % value, it can also determine the support area (10 % to 90 % interval), or the slope of the curve at the 50 % value, as a measure of the individual certainty of the statements: a steep curve or small interval indicates high certainty, while a shallow slope or large interval indicates lower certainty/higher uncertainty when sensing foreign bodies [13, 14].

The thickness of the thinnest color of articulating film (thickness of 8 µm) in common use has been established as a measure for defining an equivalent tactile sensibility (± 0.008 mm) [15].

Results on the tactile sensibility of implants

Active tactile sensibility is ten times poorer for complete dentures compared to natural teeth [67]. The tactile sensibility of implants, on the other hand, is similar to that of natural teeth [16, 51]. However, stereognosis remains better with natural teeth than with implant-supported restorations [4]. Edentulous patients with fixed, ceramic-veneered implant-supported restorations in the maxilla and mandible sometimes describe their bite as feeling very hard, like "biting on granite" [37]. Active tactile sensibility of dental implants is described by subjects as being rather dull and less localized compared to that of natural teeth [47].

In the passive tests, osseointegrated implants showed no pressure sensibility at very low static loads, but clear sensibility at stronger static and dynamic (= vibrations) loads (axial and horizontal). Maxillary implants showed higher stimulus thresholds compared to implants in the mandible. This can be attributed to the involvement of muscle, tendon and joint receptors during stimulus initiation at mandibular implants [78].

In the case of active tactile sensibility, which corresponds most closely to natural function, it was shown that the tactile sensibility is the same between single-tooth implants and natural contralateral teeth in intraindividual comparisons [15]. Even under anaesthesia of the natural antagonists of the implant and of the contralateral tooth the tactile sensibility is still very fine and intraindividually equivalent between implant and tooth [13].

However, the active tactile sensitivity of implants differs between individuals and varies between 2 µm and 54 µm with a mean value of 21 µm [15]. The slope of the tactile sensibility curves of implants is flatter than that of control teeth in intraindividual comparisons. This means that the tactile sensibility of implants is slightly less reliable than that of natural teeth [16].

The implant surface and implant geometry, i.e. implant length and thickness, and thus, the size of the bony attachment around the implant, have no effect on tactile sensibility. Likewise, gender and age have no effect [15, 16]. With regard to the dependence of tactile sensibility on age, Wedig [75] was the first to differentiate between implants and natural teeth: for natural teeth, the tactile sensibility thresholds increase the older the subjects are. Conversely, in the case of implants, there is no correlation between tactile sensibility and age. The interocclusal tactile sensibility of implants corresponds to that of teeth in older subjects [15].

The difference between active and passive tactile sensibility of implants is explained by the fact that active tests stimulate different receptor groups, whereas the passive method is designed to selectively target receptors in the periodontal ligament, which are absent in the implant region following tooth extraction [25]. The forces that occur under function, e.g. when chewing on the implants, are significantly higher than the lower forces that could be determined as threshold values in passive tactile sensitivity tests. [40].

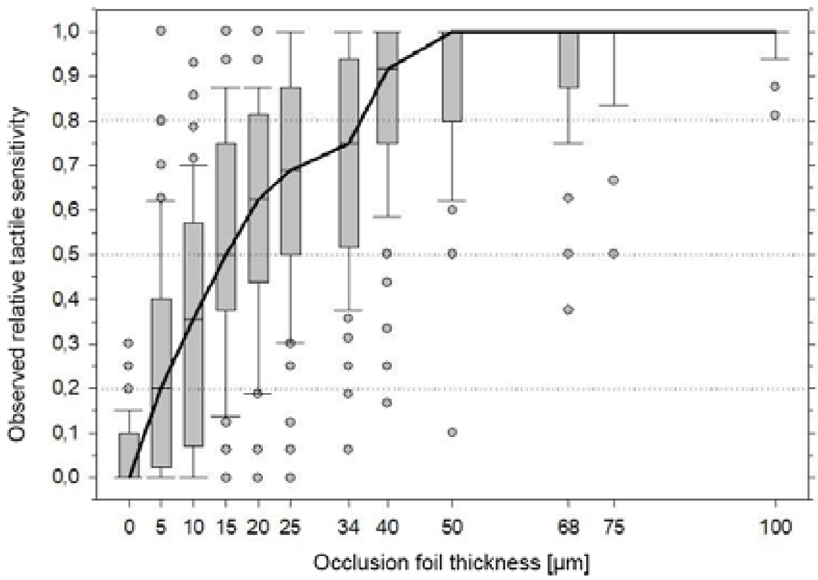

Figure 4 Representation of the results of a sample on the active tactile sensibility of implants. The 50 % value of correct results is defined as the threshold value of tactile sensibility. The 50 % threshold is reached using 15 µm occlusion foil.

For fixed restorations, active tactile sensation was slightly poorer when two implants occluded against each other than when one implant functioned against a natural tooth [1]. Some authors describe that there is a noticeable improvement in tactile sensibility as the implant's functional life increases [1, 40, 44]; however, other studies which used vibration tests did not find these differences [24]. Thus, there seems to be a phase of individual adaptation when it comes to tactile sensibility, which is also known from extensive prosthetic treatments [36, 40, 50].

Explanatory approaches to the physiology of tactile sensation with implants

The physiological basis for the tactile sensibility of osseointegrated implants, summarized under the term "osseoperception", has not yet been definitely clarified. In principle, two different theories exist:

Theory 1: activation of receptors found in local bone

Theory 2: activation of more distant receptors

Theory 1: The involvement of bone innervation in mechanical sensations remains disputed [20]. The function of bone innervation may be limited to only vasoregulatory and bone remodeling processes. Most nerve fibers have free nerve endings in bone which are connected to the endosteum, blood vessels or connective tissue components. These free nerve endings may also be able to respond to pressure and pain stimulation. Sisask et al. found a high density of neuropeptides in bone marrow [62]. Experiments on dogs have demonstrated that implant materials are abundantly surrounded by nerve fibers in the region of the implant-bone interface [21, 74]. Similarly, numerous unmyelinated and myelinated nerve fibers have been found on explanted dental implants from humans [11]. It was found that more nerve fibers were present at the peri-implant bone site than in the rest of the edentulous jaw region [20]. Immediate implant placement and immediate loading seem to result in increased nerve attachment at the implant site in comparison with concepts of delayed implantation [21]. This has given rise to the hypothesis that nerves originate from the periodontal remnants of extracted teeth, thus implying, that lower tactile sensibility of implants is to be expected after a longer post-extraction period [74]. However, the postulated re-

Figure 5a Clinical example showing the relationship between occlusion and ceramic chipping. Initial situation: cusp-to-cusp occlusion at implant crown 16 and tooth crown 46.

Figure 5b Buccal view of the situation after the chipping of the ceramic veneering at the tip of the mesiobuccal cusp of 16.

Figure 5c Occlusal view of the situation after the chipping of the ceramic veneering at the tip of the mesiobuccal cusp of 16.

Fig. 1–5: Norbert Enkling

lation of tactile sensibility to the time interval between tooth extraction and implant placement could not be confirmed in recent studies [16]. The remaining periodontal nerve structures do not appear to have any relevance with respect to tactile sensibility at the implant sites in the end. This is because implants placed in iliac crest grafts, in which periodontal structures could not be present, achieved results equivalent to those of implants in the local bone [49].

When passive tactile sensibility was tested with and without local infiltration anesthesia of the peri-implant tissue in the presence of an unscrewed abutment, so as to exclude any possible contact with the soft tissue, no effect on the sensibility threshold values during static and dynamic loading of the implants was recorded. Moreover, the tactile sensibility of natural teeth was significantly poorer under soft tissue anesthesia. This means that the anesthesia switched off peri-implant receptors of the gingiva, mucosa and periosteum, and consequently, the unchanged tactile sensibility indicates a response of more distant receptors. In the case of static loading, the results indicate that anesthetized teeth and implants reach approximately the same values, namely about 6 Ncm [78]. Using a neurophysiological test set-up in humans, in which the implants were electrically stimulated, an electroencephalogram (EEG) clearly revealed a response in the brain, which could not be reduced even by surface anesthesia of the peri-implant mucosa. The peri-implant mucosa therefore appears to play no or only a subordinate role in the phenomenon of osseoperception [70]. In the case of single-tooth implants, periodontal structures of the natural antagonists and of the natural adjacent teeth probably contribute to the tactile ability: in an animal experiment, Bonte et al. found that touching osseointegrated implants resulted in a trigeminal reflex response which was dependent on the presence of residual teeth. They concluded that the origin of the inhibitory reflexes of the masticatory muscles after implant loading could be attributed to the activation of the periodontal receptors of the adjacent residual teeth [3, 63]. The relevance of periodontal receptors of natural antagonists which are involved in osseoperception is again questioned by other study results: In comparing the active tactile sensibility of single-tooth implants with that of natural teeth on the contralateral side, the anesthesia of the natural antagonists resulted in an equivalent tactile sensibility of the of the implant-side and the contralateral natural-tooth side [13].

Theory 2: Jacobs et al. assume that the cause of osseoperception are responses from more distant proprioceptors and exteroreceptors, which are evoked via activation of the bone [23].

The subjective pressure sensation of implants appears to be less accurately localized compared to that of natural teeth in passive tactile sensibility testing and it is perceived by subjects as being transmitted further into the skull. Thus, Schulte's research group from Tübingen attributed the tactile capacity of ankylosed implants to a deformation of the peri-implant bone and an associated expansion of the periosteum [60].

The transmission of mechanical stimuli can occur due to a shift of interstitial fluid in the fine tubules and lacunae of the cancellous bone, in addition to deformation of the bone [7]. The periosteum is highly innervated and substance P, which is thought to be responsible for pain sensation to a certain degree, is present in large quantities in the periosteum [73]. The periosteum contains many free nerve endings that are important for the transmission of pain, as well as Golgi-Mazzonic corpuscles that respond to pressure sensations [58]. The periosteum of the facial bone contains mechanoreceptors that respond to pressure and expansion of the periosteum, masticatory muscles, and skin [57]. In addition, the tendon and muscle spindles [55] as well as those receptors in the temporomandibular joint that correspond to the Pacini type must also be taken into account for the tactile sensibility.

In summary, the very fine active tactile sensibility of dental implants is probably due to the activation of muscle and tendon spindles and receptors in the adjacent periosteum [2]. The phenomenon of osseoperception could be traced in neurophysiological studies using fMRI: passive loading of teeth and implants were compared at 1 Hz. After tooth extraction and implant placement, a plastic change appeared to take place in the brain: stimuli at the implant site resulted in the activation of both the primary and secondary somatosensory cortex areas [19, 77].

Clinical relevance

For the clinically practicing dentist, the measure of active tactile sensibility is more relevant than the measure of passive tactile sensibility; in practice, it is easier to work with data in “mm” than with force data in “N” [65]. Premature occlusal contacts and the associated implant overloading are discussed as possible causes for implant failures [12, 22, 30, 31]. Occlusal pre-contacts of approximately 100 µm or more can result in a clinically damaging loading effect according to the studies of Falk et al. [17] and Richter [53]. Yet, this negative effect of occlusal pre-contacts on the osseointegration of implants is disputed in other studies: Miyata et al. found no negative effects on bone with artificially placed interferences of up to 250 µm in an implant trial on monkeys [42].

However, under peak occlusal loads, static and dynamic premature occlusal contacts may exceed the mechanical properties of the veneering ceramic, and thus, favor the chipping of the ceramic veneering (cf. Figs. 5a–c). In order to detect these pre-contacts, occlusal paper or foil can be employed for staining purposes. Yet, the staining of premature occlusal contacts and the interpretation of the staining marks is non-trivial, as it is difficult to stain occlusal contacts, especially on smooth ceramic surfaces [76]. Moreover, the intensity of occlusal contact staining does not necessarily correlate with the strength or force of the occlusal contact. Very strong contacts do not stain, but rather scatter the color pigments to the periphery of the contact zone [28].

Since the interocclusal tactile sensibility of natural teeth and implants is very fine, and in part even finer than that of the thinnest occlusal foil (8 µm), it seems advisable to ask patients if they are comfortable with the restoration during the try-in appointment; more specifically, this means asking them about their subjective feeling of whether or not the restoration has the correct height [27]. The interocclusal tactile sensibility of teeth and implants, i.e. the osseoperception, thus indicates the degree to which the occlusal surfaces of teeth and restorations should be ground, so that no more occlusal interferences are sensed by the patient. According to the present study, this requires a level of accuracy down to well below 100 µm.

Conflict of interest

In the past, Prof. Dr. Norbert Enkling has given paid lectures at scientific conferences and lectures with workshops for implant companies such as Nobel Biocare, SIC Invent, Dentaurum Implants, 3M Espe and Condent.

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Photo: Norbert Enkling

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