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Tactile sensitivity of natural teeth

A clinical-experimental study

(Tactile perception of natural teeth, with literature review)

Dissertation

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submitted by:
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from Solingen
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Abstract

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Tactile sensitivity of natural teeth
A clinical-experimental study

In two experimental series, the tactile sensibility of natural antagonistic teeth was investigated.

In the first series, 109 subjects were tested using aluminium oxide particles of different sizes, uniformly distributed in yogurt. An absolute threshold value of 15 µm was determined. Male subjects detected slightly smaller foreign bodies than female subjects. Most participants were able to improve their threshold values through practice; however, they were not able to reduce them voluntarily.

In the second experimental series, tactile sensibility was assessed using copper foils of varying thicknesses. The median absolute tactile threshold values of 70 tested pairs of incisors, premolars, and molars amounted to 10 µm, whereas the corresponding value for canine tooth pairs was 20 µm.

Calculation of the 50% detection threshold yielded values of 29 µm for incisors, 63 µm for canines, and 17 µm for both premolars and molars. No sex-related differences were observed.

The two experimental series assessed different aspects of tactile sensibility. No statistically significant associations were found between tactile performance and age, time of day, tooth alignment, the extent of sliding movement between centric relation and maximum intercuspal position, or the restorative status of the teeth.

Dedicated to my parents

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1. Introduction

The stomatognathic system is understood as a biological functional circuit in which all parts influence one another (31). Consequently, pathological changes in individual areas can impair function in other parts of the system. Dysfunctional conditions are associated with disturbances of the morpho-functional equilibrium in the masticatory system (30, 68, 69, 89, 90, 91).

The teeth occupy a central position in the neuro-reflex control loop (6) as the actual tools of the masticatory system (85). They are responsible for tasks relating to food intake and processing, speech, the detection of foreign bodies, the maintenance of jaw posture and aesthetics (12, 68, 69, 85, 89, 91, 125, 134, 159). Whilst, under feedback-controlled central nervous system regulation, the masticatory muscles, jaw joints, and ligaments perform and limit the so-called ‘free’ movements of the mandible, antagonistic tooth contacts influence mandibular motor function during occlusion with the aid of occlusion (12, 16, 20, 26, 29, 36, 37, 40, 42, 43, 54, 55, 68, 69, 89, 90, 91, 94, 103, 104, 110, 123, 133, 134, 135, 140, 142, 147, 151, 156, 166, 169).

As early as 1857, PEASLEE (125) had recognised the fine tactile sensitivity of the teeth, which SIGMUND (154) described in 1867 as “modified tactile tools”. Even the slightest occlusal interferences are perceived as sources of disturbance and localised during maximum intercuspation or during tooth-guided movements (36, 58, 78, 104, 118, 137, 161, 164).

2. Statement of the problem

Occlusal harmony or disharmony influences the functional efficiency of the stomatognathic system (“form factor”, KROGH POULSEN). It is therefore important to know in which range changes to the occlusal relief already prove to be disturbing factors. An occlusal interference will, of course, only become an obstacle when the patient registers it consciously or unconsciously. However, this is likely to depend on the size of the contact threshold of the “tactile organ tooth" (SIGMUND 154). This sensory threshold is the practical guideline that dictates the accuracy of occlusal integration when fitting dentures, fabricating fillings or the degree of equilibration in cases of functional disorders. The fine tactile sensitivity of the teeth thus determine, among other things, the necessary care required in the dentist’s clinical practice. The discriminatory ability of the odonto-periodontal receptor apparatus (102) and of the masticatory system as a whole can be tested in quite various ways: For example, it is possible to determine the maximum load limit of teeth by biting down on test specimens composed of various materials (196, 7, 106, 112, 117, 162).

In contrast, the localisation ability of the dentition is tested by comparing a light load on various teeth with the patient’s subjective perception (58, 78, 118, 125, 161, 164).

The discrimination threshold can be determined, on the one hand, between forces of varying intensity (8, 9); on the other hand, it is possible to measure the threshold value between test specimens of varying thickness (2, 16, 19, 20, 80, 104, 105, 110, 111, 140, 156, 169, 176, 177 – see Table 4) or by biting down on objects of varying consistency (102, 105).

The addition of calcium carbonate (105) or small steel balls (119, 120) to test food allows the reaction of periodontal and oral mechanoreceptors to changes in the structure of the food to be investigated.

The fine tactile fine sensitivity of the teeth corresponds, on the one hand, to the "minimum load threshold". To determine this, a tooth is subjected to an increasing force until the subjective touch threshold is reached (13, 29, 39, 41, 61, 71, 74, 99, 101, 105, 111, 113, 115, 162, 163, 164, 171, 175 - see Table 1).

On the other hand, tactile fine sensitivity can be regarded as the "tactile sensitivity" (THEIL) of the teeth. It is determined by measuring the thickness of a foreign object that can just about be perceived between natural opposing teeth. Thin wires (67, 87, 9, 167) or narrow strips (16, 1081, 155, 9, 170 - see Table 2).

The tactile sensitivity of a natural tooth, defined as its response to a slowly increasing load, is physically measured in newtons (1 N = 1 kg m/s^{-2}). For dental practice, this is of more theoretical significance.

However, if one defines the tactile sensitivity of natural teeth as the thickness of a foreign body that can just about still be felt between antagonistic teeth, this results in a measurement that can be expressed in millimetres or micrometres. Determining such a threshold value therefore seems to be of greater clinical interest, as it can provide us with concrete information regarding the range of the required adjustment in dental work.

Author	Front-teeth (mN)	Canines (mN)	Pre-molars (mN)	Molars (mN)	Method/ Direction of loading
Edel et al. 1975	> 15	--	--	--	electronic converter, 50% threshold
Gneupel-Greiz 1951	> 10	> 20	> 30	> 59	v. Frey sensory hairs, axial
Herholz 1978	> 4	--	--	--	rotary swinger, axial
Jenz 1976	> 5	> 7	--	--	rotary swinger, axial
Johansson et al. 1976	--	< 100	< 100	--	electromechanical converter, 50% threshold
Linden 1975	15	--	--	--	electronic converter, 50% threshold
Loewenstein et al. 1955	9	18	24	44	Spring-loaded aesthesiometer, axial
Manly et al. 1952	10 axial > 5 laterally		> 78 axial > 18 laterally		v. Frey sensory hairs, axial, laterally
Mühlbradt et al. 1976	> 10	--	--	--	piezoelectric force sensor, axial
Münch et al. 1931	> 10		> 15		v. Frey sensory hairs, laterally
Stewart 1927	> 69		--	--	aesthesiometer, laterally
Wilkie 1964	> 4	13	--	--	Spring-loaded aesthesiometer, axial

Table 1

Results of studies on the determination of tactile threshold values in humans in the literature All units (rounded) have been converted to mN: 1 p ~ 9.8 mN).

Author	**Front-teeth (µm)**	**Canines (µm)**	**Pre-molars (µm)**	**Molars (µm)**	**Method/ Direction of loading**
Caffesse et al. 1973	--	--	--	16	alu-foil
Hollstein 1933	20	20	30	50	wire
Kraft 1962	20				wire, hairs, Perlon threads
Mela et al. 1965	10-62				metll-foil, 50% threshold
Siirilä et al. 1963	8-10	--	8-10		alu-foil, tin-foil
Theil 1931	50				wire
Tryde et al. 1962	--	--	10-35 (± 15)		silver-foil, 50% threshold

Table 2

Results of research into tactile sensitivity using antagonistic dental contact (literature review)

3. Aims of the study

In the following, the tactile sensitivity of natural teeth will be measured using two different methods and compared.

Firstly, the ability of the odonto-periodontal receptor system to distinguish between stimuli will be determined by detecting minute particles in food (Experiment 1). Secondly, we have determined the thickness of the metal foil that the subjects can just about feel between their teeth (Experiment 2).

As it is reasonable to assume that the results of the investigations may depend on various factors, a correlation with the following factors was also examined:

- Age and gender of the subjects
- Time of day of the examination
- Type of occlusion
- Magnitude of the sliding movement between the retral contact position and maximum occlusion
- Type of fillings and crowns.

The choice of examination method should take into account the anatomical and physiological characteristics of the masticatory system. The experimental results should also be evaluated solely from this perspective. Therefore, the fundamentals are summarised below.

4. Anatomical, histological and physiological preliminary remarks

4.1. Structure, blood supply, nerve pathways and the mechanoelectrical transduction system of the periodontium

The periodontium consists of cementum, desmodont, alveolar compact bone and marginal periodontium (48). It provides a spring-like suspension for the tooth within its alveolus. The periodontal ligament contains rhombically branched and functionally oriented blood vessels in the manner of a 'reticulated basket', as well as lymphatic vessels running parallel to them. Lymph, blood and interstitial fluid form a hydraulic fluid cushion against the dynamic stress on the tooth; they contribute decisively to its functional movement characteristics (5, 62, 63, 66, 76, 85, 145, 146, 148, 149 - cf. Chapters 4.3).

The connective-tissue syndesmosis between the tooth and the alveolar bone further consists of coarse-fibred, inelastic, shearing lattice-like, criss-crossing and undulating collagen fibre bundles in a functional arrangement, as well as oxytalan fibres. The fibres are embedded in a gel-like, amorphous ground substance and serve to transmit forces from the tooth to the bone. They characterise the initial and desmodontal tooth mobility (35, 62, 63, 76, 85, 138, 145, 148). The collagen fibres run not only between a tooth and its alveolus, but in the region of the attached gingiva one also finds transseptal fibres. These connect the supra-alveolar root cementum of one tooth to that of the adjacent tooth (146).

The thickness of the periodontal space between the tooth and the bone depends on the age and function of the tooth (21, 35). The volume of the periodontal space is 30–100 mm³, and 65-150 mm³ in multi-rooted teeth (146). It also contains nerve branches of the trigeminal nerve as terminal branches of the superior dental plexus and the inferior dental plexus, including the sensory endings. It is now assumed that the pulp of the tooth is merely capable of transmitting nociceptive stimuli, whereas the receptors for tactile sensitivity are located in the periodontium and not in the hard dental tissue (1, 2, 11, 13, 15, 18, 41, 53, 60, 62, 67, 79, 85, 87, 99, 111, 126, 127, 132, 150, 154, 155, 156, 168, 170, 171, 173, 174).

The somatosensory and autonomic innervation of the periodontium is ensured in two different ways: thicker nerves comprising approx. 8–20 fibres (145) enter the periodontal ligament in the apical region of the alveolus. They extend both towards the root apex and towards the marginal periodontium. Further, thinner trunks comprising approx. 8–10 fibres (145) reach the desmodont via the lamina cribrosa of the alveolar bone. From there, they run on the one hand to the marginal gingiva, and on the other hand back towards the apex (2, 4, 10, 11, 15, 25, 35, 75, 82, 98, 136, 146, 155, 174). There are unmyelinated fibres between 0.5 and 4 µm in diameter and myelinated fibres ranging from 1 to 16 µm in diameter. Nerve conduction speeds vary between 24 and 83 m/s (3, 45, 46, 96, 162).

There is no consensus regarding the nature of the nerve endings. FALIN (33), KADANOFF (75) and WEILL et al. (174) are unable to identify any specific endings; BRADLAW (10), FRANK et al. (34), LAUTENBACH (97), LEWINSKY et al. (98), SIMPSON (157) and van der SPRENKEL (160) also find no encapsulated receptors, but adjustable loops and bulbous thickenings. SCHOUR (145) reports spindle-shaped end organs and Pacini corpuscles, BERNICK (4) and KIZIOR et al. (82) found free nerve endings and ovoid structures. According to CORPRON et al. (22), FRANK et al. (34), GRIFFIN and HARRIS (45), RAPP et al. (136) and van der SPRENKEL (160), three types of mechanoreceptors in the periodontium must be distinguished from one another. Thus, GRIFFIN and HARRIS describe:

1. Simple mechanoreceptors (Type I) measuring 10 × 10 µm, which are regarded as isolated receptors of individual myelinated fibres. The nerve enters the cylindrical receptor and only loses its myelin quite late. The fibre splits and forms a network that is separated from the myelinated portion of the nerve by septa. The outer capsule of the receptor is embedded in loose connective tissue. As the organ can therefore yield to pressure, it may belong to the fast-adapting nerve units. The nerve ending is supplied by diffusion; its threshold is low (45., 47, 56).
2. Compound mechanoreceptors measuring 35 × 45 µm (Type II) resemble muscle spindles in structure. The receptor arises from a myelinated nerve that first branches into several arms. These fibres lose their myelin and converge into terminal rings. They surround an adjacent unmyelinated nerve fibre, including some intraneuronal collagen fibres. The capsule of this structure lies embedded in extracapsular collagen fibres, which the receptor follows in the longitudinal direction. The receptor, which may be slow-adapting and spontaneously discharging, reacts to changes in length in the periodontium. It is supplied by an artery (4, 46, 47).
3. Free nerve endings arise from myelinated and non-myelinated nerves. They terminate as simple axonal thickening or freely in the form of tree-like branching (44, 45, 57, 82).

4.2. Distribution of receptors in the periodontium

HANNAM (51) and STEENBERGHE (162) considered the distribution and the number of receptors in the periodontium to be unclear. HERHOLZ (61) finds no uniform effect of a root-apical resection on the tactile sensitivity of the anterior teeth and therefore assumes that the mechanoreceptors are evenly distributed across the entire root surface. Teeth with apical changes as well as periodontal destruction show, according to MELA et al. (108), no difference in tactile sensitivity compared to periodontally healthy teeth. The minimum pressure threshold is the same in patients with and without alveolar bone loss according to EDEL et al. (29). HOLLSTEIN (67), on the other hand, records lower tactile sensitivity in teeth with root-tip amputation as well as those with loss of the alveolar ridge. Histological studies by BERNICK (4), BYERS et al. (15) and FALIN (33) suggest that nerve endings are predominantly located in the apical region,

4.3. Physiological movement mechanisms of the periodontium

The healthy periodontium possesses specific movement characteristics, which guide the tooth along predetermined paths and can only be altered unpredictably by the direction of the load (59, 84, 1149, 124). The degree of tooth mobility depends on the insertion surface of the desmodontal fibres, on the shape and number of roots, and on the structural and biophysical properties of the periodontium (138). It is inversely proportional to the surface area of the respective tooth root (95). Forces acting on the tooth exert a direct effect via the root on the complex hydrodynamic apparatus (62) and thus on the receptors. As the loading rate increases, the fluid resistance of the terminal fluid pathways increases, i.e., the periodontium reacts ‘more strongly’. Dynamic impacts and high-frequency vibrations are therefore primarily absorbed by the fluid system (5, 62, 84, 114).

Static and quasi-static loads (85) lead up to approx. 120 p load and tooth movement of approx. 80 µm (63) to a tightening of the collagenous periodontal ligament fibres. This is associated with interperiodontal fluid displacement (initial desmodontal mobility). From a load of approx. 120 p, the elastic deflection of the tooth and alveolar bone also comes into play (secondary periodontal mobility) (95, 130, 138). Tooth movements occur during function, particularly lingually and distally (anterior teeth mesially) as well as cranially or caudally. The magnitudes are approximately 60 µm / year for empty mastication, approximately 10 µm for the closing of the dental arches, and approximately 30 µm/year for chopping movements (157). The mobility of a tooth is also determined by its position within the alveolus. During sleep and in the absence of antagonistic contacts the tooth assumes an extruded position via the terminal nerve pathway. This can increase its degree of looseness. Over the course of the day, the tooth loses mobility as it assumes a balanced position between intruding and extruding forces (65, 121, 129). Without the contact (palpation) process and the continuous control during the subsequent increase in pressure, physiological tooth movement would not be possible at all (62).

4.4. Mechanical-electrical transformation system of the skin

In the skin, three main types of mechanoreceptors have been identified as the histological equivalents of the stimulus.

1. *Merkel cells* are pressure receptors which, as so-called intensity detectors, measure both the intensity and the duration of the stimulus. They adapt slowly. and are innervated by myelinated afferent nerve fibres of group II.
2. *Meissner's corpuscles* are touch receptors. They are regarded as velocity detectors that adapt moderately quickly. The receptor only transmits stimuli during movement. Group II fibres conduct its impulses to the CNS. The vibration receptors transmit vibration stimuli via Group II axons, which are greater than 60 Hz.
3. The acceleration detectors – which histologically correspond to the *Vater-Pacini corpuscles* – adapt very quickly and respond – regardless of the stimulus intensity – with a single impulse. The mechanosensitive free nerve endings function in the skin as threshold detectors. They transmit weak, moving mechanical stimuli, which are relayed at approximately 1 m/s via Group IV fibres

The threshold values for deformation are 0.5 µm, for the tactile receptors of the frog at 2 µm and for the muscle spindles of cats at approximately 10 µm (17). The transitions between touch and pressure are fluid, as everyday mechanical skin stimuli normally involve several receptors; the sensations evoked cannot, however, be attributed to just one type of receptor (17, 144). STEENBERGHE (162) states that the functional properties of the periodontal receptors are comparable to those of the receptors in the rest of the body.

4.5 Sensory physiology of the periodontium

Receptors are specific nerve cells that transmit information about states and/or changes in state on the body's surface (exteroceptors) or within the body (proprioceptors) to the central nervous system. Each receptor responds specifically to a particular type of stimulus (receptor specificity), whereby the stimulus that is most effective in each case is the 'appropriate' stimulus for the receptor (17, 27).

Mechanical stresses on the dental crown lead, via changes in pressure and tension in the desmodont, to stimulation of the root dermal receptors (2, 45, 46, 49, 50, 51, 53, 56, 57, 72, 74, 77, 79, 82, 107, 116, 126, 127, 172, 178, 179, 180). In this process, up to three adjacent teeth can trigger a response in a single nerve unit (51).

When the direction of the force coincides with the axis of maximum receptor sensitivity, the shortest latency, a maximum frequency of action potentials and minimal stimulus thresholds are observed. This results in a certain dependence between the stimulus response and the direction of the stimulus (2, 23, 49, 50, 51, 72, 74, 79, 82, 116, 126). There are nerve units that respond to only one direction of tooth loading and others that respond to all directions (51).

Mechanical deformation is the appropriate stimulus that depolarises the cell membranes of the mechanoreceptors; a ‘receptor potential’ is generated, which persists for as long as the stimulus is applied. The effect of the stimulus diminishes with prolonged constant stimulation; that is, the receptor cell ‘adapts’ at its characteristic rate (17, 27, 72).

If the depolarisation of the receptor reaches a certain minimum level, i.e. its ‘stimulus threshold’, then one or more action potentials are triggered in the associated nerve – depending on the duration of the stimulus. However, the transmission mechanism that converts mechanical energy into changes in electrical membrane potential has not yet been fully elucidated (17).

The axon transmits the action potentials to the CNS, where they are shaped at the individual synapses of the various neurons by phenomena such as divergence, convergence, lateral feedback inhibition and habituation. This generally promotes the transmission of weak stimuli and inhibits that of strong stimuli (38, 53, 139, 143, 144). The stimulus intensity thus continuously controls the level of the receptor potential. Above a certain minimum threshold, it determines the frequency of action potentials. The adaptation of the receptor potential – a change in the receptor’s sensitivity – is reflected in a steadily decreasing frequency of the axon’s action potentials (38, 139, 143, 144).

The absolute stimulus threshold of the tactile sensitivity of natural teeth can be determined by identifying the smallest stimulus intensity to which the mechanoreceptors in the desmodont, via the teeth, respond with a change in the frequency of their action potentials. In animal experiments, the action potentials can be recorded directly from the dental nerves. In this way, load thresholds can be determined (2, 72, 74, 126, 172 – see Table 3) and the response patterns of the various receptors investigated (49, 50, 51, 82, 107, 116, 126, 167, 180). It is also possible to measure the tooth deflections that trigger these action potentials (178, 179).

Author	**Species**	**Tested tooth**	**Threshold (mN)**
Jerge 1963a	cat	all teeth	type I > 10 type II > 20
Johannson et al. 1976	human	canine, premolar	100
Kawamura et al. 1966	cat	canine	20
Pfaffmann 1939a	cat	canine	20
Wagers et al. 1960	dog	canine, molar	20
Yamada et al. 1969	dog	front teeth, canine, molar	40 higher value

Table 3

Results of the electrophysiological pressure threshold test (1 mN = 0,1 p).

However, this stimulus threshold does not always have a constant value. It depends not only on the intensity of the stimulus, but also on how the stimulus intensity changes over time. If a stimulus that is initially subthreshold but gradually intensifies is applied very slowly, this raises the threshold value (“accommodation”, "creeping in" 17, 38, 139, 162).

Electrophysiological investigations further showed that there are fast- and slow-adapting as well as "spontaneously" firing nerve units in the desmodont (1, 49, 50, 51, 72, 79, 82, 107, 116, 1229, 127, 167, 173, 180) According to most authors, the stimulation thresholds of the slow-adapting units appear to be low (10–30 mN axially; 49, 72, 74, 79). The firing frequency of the units is proportional to the logarithm of the pressure (180). They respond more precisely to higher stimulation frequencies than fast-adapting nerve cells (79, 127). It is possible that the compound receptors (type II) described by GRIFFIN and HARRIS (45, 46) are slow-adapting, as they are tightly enveloped by the collagen fibres of the desmodont and connected in parallel with them.

In contrast, fast-adapting nerve units do not respond to a new stimulus for several seconds (107, 127). According to JERGE (72), their stimulus threshold appears to be higher than that of the slow-adapting cells (according to HANNAM [49]: 20–60 mN axially; according to KAWAMURA et al. (79) 294 mN). They discharge primarily at the onset of a stimulus (49, 116). The anatomical correlate may be found in the bulbous simple mechanoreceptors (type I), as these are surrounded by loose connective tissue and can evade pressure (45, 47, 56).

In addition, there are also spontaneously firing nerve units that respond to a load of 20–50 mN (173). Pressure applied in a specific direction increases their firing rate, whereas pressure from the opposite direction reduces it (116, 173). The causes of spontaneous discharges may lie in a slight mechanical deformation of the receptors (50, 107, 116). STEENBERGHE (162) attributes the cause of spontaneous discharges to a constant tension in the periodontium, which is transmitted to the receptors. According to GRIFFIN and HARRIS (45), the compound receptors (type II) are considered potential triggering receptors, as these have their own blood supply.

According to KIZIOR et al. (82), the individual pressure-sensitive receptors have different threshold values. The pressure sensitivity in the most sensitive direction varies between 10 and 30 mN (1 p ~ 9.81 mN) (74), whereby the threshold properties of the receptors are determined by their viscoelastic environment (162).

YAMADA (178, 179) investigated the relationship between the extent of individual tooth movement and the triggering of action potentials. According to their findings, a tooth must be moved by at least 2 to 3 µm to trigger an action potential. Tooth movements of approximately 10 µm are required to elicit clear stimulus responses.

The human ability to distinguish between forces acting on canines is approximately 3.6 bits at the peripheral level. In the central nervous system, the flood of information is likely reduced to 2.5 bits. The subjective distinction between force magnitudes is greatest for small forces (24, 53).

The mechanoreceptors of the periodontal ligament are capable of reflexively influencing jaw muscle activity (26, 36, 37, 40, 134, 142, 147, 160, 162). In doing so, the receptors regulate the firing of trigeminal motor neurons (12, 54, 55, 77, 78, 103, 151). Thus, a jaw-opening reflex can be observed following light tapping of the teeth, gingiva or hard palate. At the same time, the jaw-closing muscles are inhibited via the muscle spindles following brief activation. The reflex appears to be involved in the regulation of masticatory processes (37, 54, 55, 151).

4.6. The role of receptors in the periodontium, masticatory muscles and temporomandibular joint in the tactile process

The question of where the receptors responsible for detecting foreign bodies are located does not yet appear to have been definitively resolved. The literature is contradictory on this point (see Table 4).

Extensive research has confirmed that a tooth is displaced within its alveolus when subjected to load. This stimulates the mechanoreceptors of the periodontium, which are involved in neuromuscular reflex regulation (see Chapters 1, 4.3 and 4.5). The flow of information is greatest under low loads and then approaches a maximum value (24, 53). RIIS et al. (140) and SIIRILÄ et al. (156) conclude from their studies using thin foils between opposing pairs of teeth that the periodontium plays a significant role in the detection of small foreign bodies. The smaller the foreign body, the greater the need for the tactile sensitivity of the periodontium. Studies by CAFFESSE et al. (16) and KAWAMURA et al. (80) confirm this view.

When using very thin foils, control contacts may well occur between opposing teeth – depending on the position of the teeth – on teeth not involved in the probing process. Only the opposing teeth, where the foil lies between the contact points, are pressed deeper into the alveolar socket than their neighbours, by approximately half the thickness of the foreign body. When the mouth is opened wide and contact between the teeth is mediated solely by large foreign objects, the ability to distinguish between different thicknesses can inevitably no longer be mediated exclusively by the periodontium. CHRISTENSEN et al. (20) and MORIMOTO et al. (110), amongst others, conclude from this that the periodontium is not responsible for this ability to distinguish between thicknesses at all.

Other authors assume that the ability to distinguish between foreign bodies of different thicknesses is attributable solely to receptors in the masticatory muscles (19, 20, 110). Kubota et al. (94) found muscle spindles in all masticatory muscles except the mylohyoid muscle and the anterior belly of the digastric muscle. Muscle spindles in cats respond to changes in muscle length from an extension of approximately 10 µm (17). MANLY et al. (105), RIIS et al. (140) and SIIRILÄ et al. (156) also consider it likely that the masticatory muscles are involved in tactile processes.

THILANDER (169) investigated the innervation of the temporomandibular joints and found free nerve endings, Ruffini corpuscles, modified Vater-Pacini corpuscles and Golgi tendon organs. Following unilateral or bilateral anaesthesia of the temporomandibular joints, she observed a drastically reduced perception of mandibular position. THILANDER and RANSJÖ et al. (135) therefore believe that the temporomandibular joint alone is responsible for the perception of mandibular movement. In contrast, CAFFESSE et al. (16), KAWAMURA et al. (80), MANLY et al. (105) and RIIS et al. (140) consider that the temporomandibular joint is merely involved in the ability to distinguish between foreign bodies of varying thickness.

Author	Type of measurement method	Thickness of the foils / Size of mouth opening (µm + mm)	Localisation of the receptors		
			TMJ	JM	Perio
Caffesse et al. 1973	Aluminium-foils	8-100 µm	x		x
Christensen et al. 1976	Copper-foils	2-3 mm		x	
Christensen et al. 1977	Resin rods	8-12 mm 43-47 mm		x	
Kawamura et al. 1960	Steel wire	1-5 mm	x		x
Manly et al. 1952	Discs	5-6 mm	x	x	
Morimoto et al. 1976	Rods	vertical dimension ± 8 mm		x	
Ransjö et al: 1963	Ruler	Between the rest vertical dimension and the fully open position	x		
Riis et al. 1970	Plastic foils	12-100 µm	x	x	x
Siirilä et a. 1972	Tin foils / caliper	0,5 mm to max. opening minus 10 mm		x	x
Thiladner 1961	Ruler	Between the rest vertical dimension and the fully open position	x		

Table 4

Studies on the ability to distinguish between foreign bodies of different sizes in the anterior dental region at various mouth openings.

(TMJ = Temporomandibular joint; JM = Jaw muscles; Perio = Periodontium)

4.7. General subjective sensory physiology

The preceding text described the fundamentals primarily from an anatomical and physiological perspective. There is no doubt that, when measuring tactile sensitivity, one must also take into account the subjective perceptions of the participants. The four fundamental dimensions of any perception are temporality, spatiality, quality and intensity (27). The four aspects of tactile sensation are stereognosis (spatial perception), topognosis (location perception), projection (‘the tooth is the mediator’) and perception (13). The ability for oral spatial perception declines with age (14, 100).

The sensations must be assessed by the test subject, who thereby sets their own guidelines for determining the intensity of these sensations (“self-metric” measurement method – SKRAMLIK (158). Nevertheless, a high degree of agreement is observed between the subjectively estimated intensity of sensation and the objectively determined responses of the sensory neurons. Thus, even in subjective sensory physiology, subtle quantitative measurements are possible (27, 162).

5. Own Research

5.1. Selection and dental findings of the study group

The studies were carried out on students and staff at the Department of Dental, Oral and Maxillofacial Diseases at the University of Bonn. A prerequisite was that the subjects either had full dentition, had gaps closed with fixed replacements, or had only space maintainers with dental support in all four quadrants. The periodontium had to be clinically healthy and must not show any significant deterioration. The degree of tooth mobility was therefore within physiological limits. Participants with functional complaints, as well as those with fillings or dentures that had not yet been incorporated, were excluded from the study.
A total of 109 participants took part in the first examination (palpation of minute particles in food), of whom 55 were females and 54 males. The age distribution is shown in Table 5.

In order to rule out the possible influence of other parameters on the study results, we recorded additional findings:

- A lateral drift between the retral contact position and the maximal intercuspal position was measured using a ruler placed between the labial surfaces of the upper and lower anterior teeth (see Table 6). In 26 participants, the lower jaw deviated to the side.
- The findings also covered tooth alignment during laterotrusion (see Table 7).
- Dental care for the group is shown in Table 8. Thirty-eight of the subjects had previously undergone orthodontic treatment.

Age group (years)	Number of participants
10 - 19	8
20 - 29	57
30 - 29	31
40 - 49	7
50 - 59	6

Table 5

Age distribution of the participants of the yoghurt tests.

Range of sliding movement (mm)	Number of participants
≤ 0,5	55
0,5-1	40
≥ 1	13

Table 6

Relationship between centric relation (CR) and maximal intercuspal position MIP).

Tooth guidance	Number of participants
Front and canine protected articulation	11
Group function	56
Initial group guidance, later canine protected articulation	33
A combination of different types of guidance on the left and right	7
Balance contacts	59
Hyperbalance guidance	2

Table 7

Types of tooth guidance.

Type of dental treatment	Number of participants
No fillings or crowns	3
Resin/amalgam fillings	32
Inlays / onlays / crowns	20
Resin- / amalgam fillings as well as inlays / onlays / crowns	22
Bridge pontics	14
Resin- / amalgam fillings, inlays / onlays, crowns and bridge pontics	18

Table 8

Dental care of the test group.

5.2. Experiment 1: Testing the sensitivity of the periodontium using foreign bodies in food

5.2.1. Selection of test specimens

To investigate sensitivity to foreign bodies in food, test specimens are required which, on the one hand, are available in a sufficiently fine range of sizes and are physiologically compatible, and, on the other hand, are not affected by moisture.

We initially considered steel balls, but these were not available in the required sizes. Furthermore, if a patient were to bite down on them unexpectedly, there would have been a risk of tooth fracture.

We therefore opted for crystallised aluminium oxide (Al_2O_3, corundum). Like Bikorit[1] and Redurit[2], this is normally used as a raw material for grinding. The materials were available to us in the following size ranges (Association of Electrocorundum and Silicon Carbide Manufacturers, 32):

Grinding material	FEPA classification	particle size rang (µm)
Bikorit	F 1200 "CS"	2.5 - 3.5
Bikorit	F 800 "CS"	5.5 - 7.5
Bikorit	F 500	11.8 - 13.8
Redurit	F 360 "CS"	21.3 - 24.3
Redurit	F 280 "CS"	35.0 - 38.0
Redurit	F 240 "CS"	42.5 - 46.5
Redurit	F 230 "CS"	50.0 - 56.0
Redurit	180	62.0 - 88.0
Redurit	120	105.0 - 125.0
Redurit	100	149.0-177.0

Table 9

Grain size ranges of Bikorit and Redurit.

The typical properties of Bikorit are high hardness and brittleness, whilst those of Redurit are

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[1] We would like to express our sincere acknowledgements to Dynamit Nobel AG, ES range, Haberstr. 2, 53842 Troisdorf-Oberlar for their kind and prompt handling of our requests and for providing the test specimens free of charge.

[2] see above

high hardness and toughness. The raw materials contain small amounts of impurities, which are bound within the grain as oxides; they are non-conductive, non-hydrating and chemically completely inert (28). A significant disadvantage of the abrasive particles for our experiments was their inhomogeneous structure, which deviated considerably from the ideal spherical shape (see Fig. 1).

We chose unflavoured yoghurt as the carrier medium for the test specimens. Yoghurt has no structure of its own that can be felt by the teeth and has a consistency that prevents gravity-induced sedimentation of the Al_2O_3[3] particles.

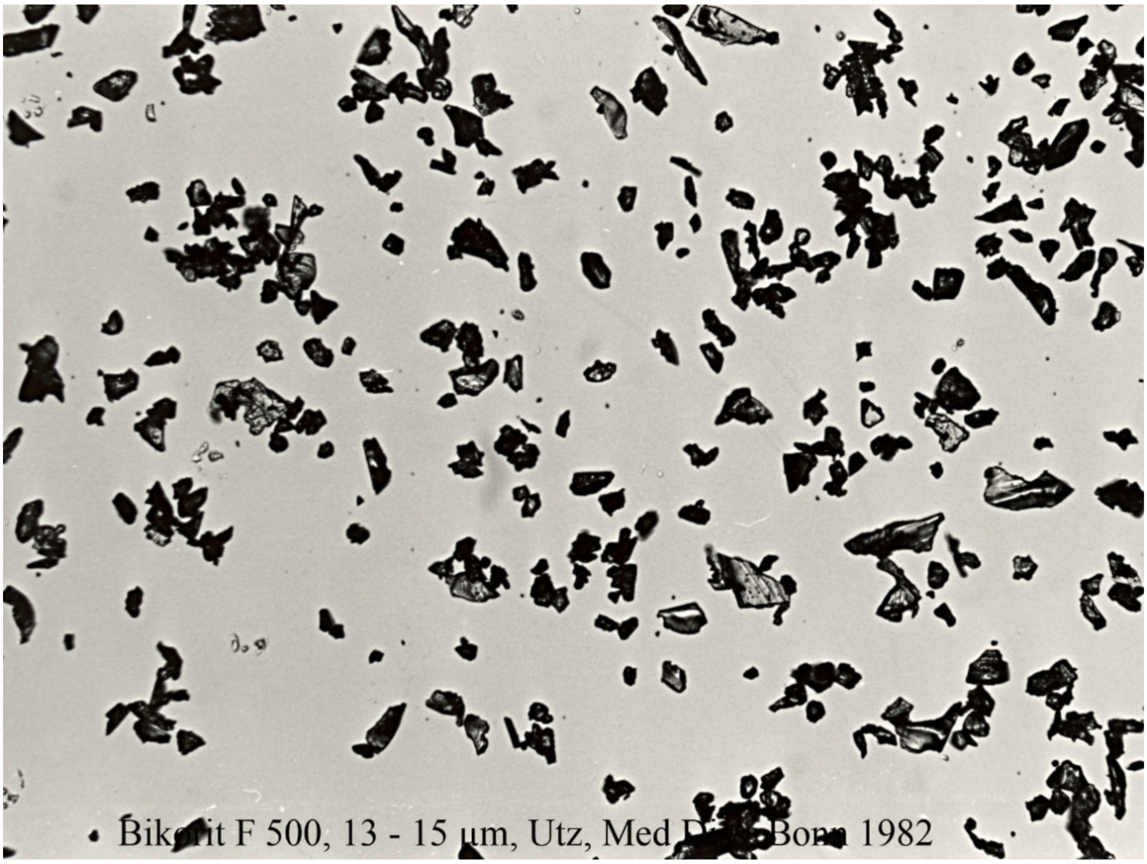

Fig. 1

Surface structure of the test specimens (range 11.8–13.8 µm)

5.2.2. Preliminary tests

In order to achieve a suitable concentration of aluminium oxide particles in the yoghurt, preliminary trials were carried out with 27 participants. Doses of 50, 100, 200, 300, 400 and 500 mg[4] of Redurit in sizes 180 SN (up to 88 pm) and F 24O ‘CS’ (up to 46.5 pm) were mixed with 125 g (= approx. 108 ml) of yoghurt using the dough hook of a standard electric

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[3] Albrecht Einkauf OHG, Mülheim

[4] Mettler E 200/9 electronic balance

hand mixer. The test subjects were asked to assess at which particle size they could detect the test specimen between their teeth. As bone conduction via the teeth to the inner ear might have distorted the results, the participants' ears were played "linear white noise[5]" mixed with "pink noise[6]" from a tape recorder[7] via headphones.[8]

On the one hand, it should be possible to detect corundum particles whenever the teeth came into contact. On the other hand, we wanted to avoid the test specimens piling up on top of one another during the detection process as far as possible. We therefore decided to regard the concentration of test specimens in the yoghurt as the 'reference concentration' – the concentration that was just about detectable by 100% of the participants. This reference concentration corresponded to 180 SN = 400 mg in 125 g of yoghurt for Redurit and 240 'CS' = 300 mg in 125 g of yoghurt for F. It was then applied to all other particle sizes of Redurit and Bikorit. In doing so, the probability for each corundum grain in the yoghurt to reach a contact point between the teeth should be equally high. To calculate these equal probabilities for the individual particle sizes, we first suspended a quantity corresponding to the reference concentration (400 mg in 108 ml) of test specimens of all sizes in a 70% sucrose solution in photometer cuvettes (Fig. 2).

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[5] White noise is a noise with a constant power spectral density within a specific frequency range, or a continuous, broadband sound that contains all frequencies audible to humans at exactly the same volume.

[6] Pink noise is a steady background sound in which the energy decreases by 3 decibels per octave as the frequency increases.

[7] Linear white noise and pink noise from the Brüel & Kjoer Type 1402 random noise generator, Copenhagen, recorded using the AIWA AD 6900 cassette recorder onto Maxell UD XL II tape.

[8] Pearless PMB 4

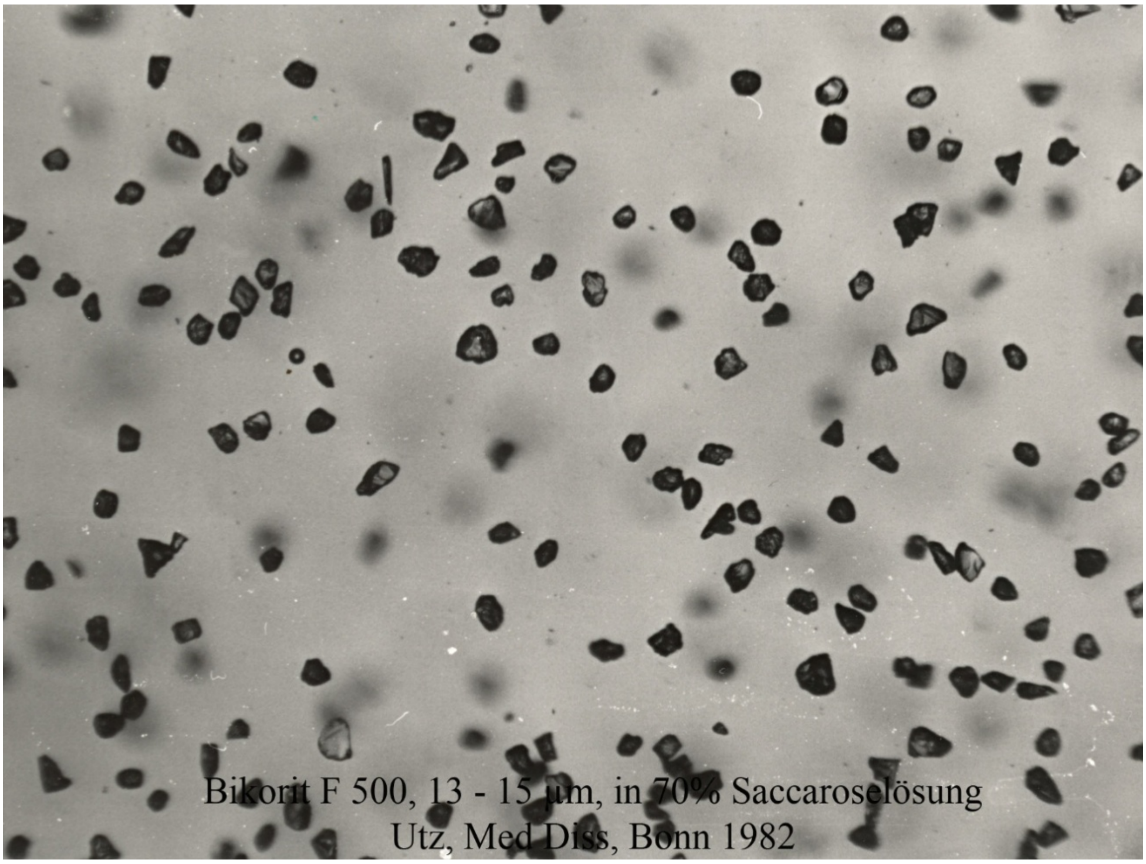

Fig. 2

Distribution of test specimens in a 70% sucrose solution

We then used a computer[9] connected to a microscope[10] via a television camera to determine the projected areas of the individual abrasive particles of a given size. The underlying idea was to determine, for each test specimen size interval, the same projected area of the corundum particles as in the reference concentration. Unfortunately, this concept could not be realized. We were only able to determine the same number of test specimens from the individual size ranges in the yogurt. We conducted tests following this pattern on the first 20 subjects.

In a second series of experiments, the test subjects assessed the reference concentration (400 mg in 125 g of yogurt) regardless of the size of the test specimens. As a rule, the test subjects were able to detect only larger test specimens when the concentration sample contained the same number of corundum particles. If, however, the concentration measure was based on the same weight of test specimens of different sizes, the test subjects were able to feel even smaller test specimens. We therefore decided to continue the test series with 400 mg of abrasive particles in 12.5 g of yogurt (= 0.3%) for all size ranges.

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[9] Wang 700, Wang Laboratories

[10] Videomat, Zeiss

5.2.3. Final experimental setup

The tests were conducted in a quiet room. Before beginning, we gave the participants a handout describing the purpose and procedure of the experiment as follows:

> **Handout describing the experimental procedure for the participants:**
>
> "Experimental procedure: Tactile sensitivity of the teeth during chewing.
>
> The purpose of the study is to determine the tactile sensitivity of the teeth.
>
> For this purpose, harmless test specimens of various sizes were distributed among different yogurt cups. By using normal chewing motions (as when chewing bread), the test subject is to determine whether there are "grains" in the yogurt that can be felt between the teeth, or whether the yogurt is "smooth," meaning no grains can be felt.
>
> The test includes yogurt cups with and without "grains." The test subject is offered a teaspoon of yogurt with or without "grains." The yogurt should not be swallowed immediately, but rather examined using bread-chewing motions.
>
> As soon as the test subject feels a test sample anywhere between the rows of teeth, they must immediately signal this to the examiner with clear nodding head movements. If no test samples were felt, at least 10 chewing motions must be performed before the final decision, and the examiner must be informed only afterward (by shaking the head).
>
> After the decision, the yogurt may be swallowed or spat out; the mouth must also be rinsed thoroughly to remove all test specimens from the teeth (use a toothbrush if necessary). The complete removal of all foreign objects should be verified by feeling the teeth.
>
> Since foreign objects between the rows of teeth can not only be felt but also heard via bone conduction, hearing must be blocked during the test using headphones and white noise. To do this, the ears must be well sealed. The headphones may be removed while rinsing."

The key points were briefly reviewed, and any questions were answered. The subjects then settled into a comfortable position in the treatment chair. Linear "white noise" mixed with "pink noise" was played as loudly as possible through headphones from the cassette tape recorder[11] into the subjects' ears.

For each experiment, ten yogurt cups containing test specimens of various sizes were available (see Table 9). The concentration was 400 mg of corundum per 125 g of yogurt,

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[11] Recorded using a Korg MS-50 synthesizer

consistent with the preliminary tests.

For each test, the participants were given a teaspoon of yogurt, and we used a new spoon for each sample. The test subjects could not see which cups the yogurt was taken from.

First, we tested with decreasing test piece sizes. In this way, the test subjects determined their individual threshold, that is, the test piece size that they could just barely feel between their teeth. Following the test in which the subjects could no longer feel the test piece, they were given another sample of their threshold size. If the subjects recognized this again, they were to test the next smaller test piece. Using this method, we verified the threshold value three times.

It turned out that some subjects were able to positively identify a particular test object size on one occasion but failed to recognize it on another. In these cases, after a total of five tests, the test object size that was positively identified at least three times was recorded as the threshold value.

To minimize methodological errors, we asked the subjects the following questions following the examination, which lasted just under thirty minutes:

1. Did you also perceive the test objects with your mucous membranes, lips, or tongue?
2. Did you hear the test objects through bone conduction, or did you only feel them between your teeth?
3. Did you primarily detect them with your front teeth, your back teeth, or both?

We tested 48 participants on a single day at various times and 24 participants on different days at roughly the same times. Only six people were tested just once. In total, we conducted 297 tests.

5.2.4. Criticism of the experimental setup

The method described in Section 5.2.3. cannot, in principle, be used to determine the tactile sensitivity of individual teeth. One of the weaknesses of the study is related to the properties of the corundum abrasive particles, which were not available in uniform sizes but only in size ranges. The reason lies in their inhomogeneous, often splintery structure, which can deviate significantly from the ideal spherical shape (see Fig. 1). A breakage caused by the abrasive particles being bitten apart during tooth contact—and thus a change in the size of the test particles—cannot be completely ruled out.

Roughness is inherent to abrasive particles. Therefore, it is possible that it was not the thickness of the test specimens but solely their surface structure that was perceived. Some participants thus reported at the end of the experiment that their teeth felt “dull.”

Since the concentration was based on the weight of the test particles of various sizes, it cannot be assumed that the distribution of the test particles in the yogurt was identical across all size ranges. Consequently, the probability of encountering a test particle when feeling around varies across the different size ranges. This is also a problem that is virtually impossible to solve due to the unequal volumes of yogurt scooped with teaspoons, the unquantifiable dilution by saliva, and the unknown distribution of the test specimens in the mouth before and during tooth contact. However, this does not seem to play a very significant role to us, as it was not the purpose of the study to compare the individual test series with one another. Nevertheless, a minor influence on the absolute level of the threshold values in the final result cannot be ruled out.

As can be seen from the preliminary tests, the threshold value can also be influenced by the number of test specimens in the carrier medium. It is therefore not solely dependent on particle size.

Whenever possible, most participants were initially scheduled three times a day (between 8 a.m. and 11 a.m., 11 a.m. and 2 p.m., and 2 p.m. and 6 p.m.). With this experimental design, a practice effect cannot easily be distinguished from a time-of-day effect.

5.3. Experiment 2: Assessment of periodontal sensitivity using metal foils between opposing tooth pairs

5.3.1. Selection of test material

Wires are not particularly suitable for assessing the sensitivity of the periodontal tissues of selected opposing tooth pairs, as it is very difficult to position them precisely over contact areas that may be limited to a single point. In contrast, narrow, thin strips can be placed between the teeth without significant difficulty.

Such foils must possess opposing material properties. On the one hand, when the teeth are closed, they should conform smoothly to the tooth surface to prevent premature contact stimuli from being triggered when the teeth come together. On the other hand, the material must be hard enough that its thickness does not change even during and after repeated probing movements of the teeth. Plastic foils are therefore not suitable. Furthermore, a material is required that does not lead to the formation of galvanic cells between gold and amalgam restorations in the mouth.

We therefore selected metal foils made of 99.9% pure copper with thicknesses ranging from 3 to 250 µm and a tolerance of ±10% for each[12]. The material properties of the copper foils used (according to specifications provided by Goodfellow Metals Ltd.) are summarized below.

Compressibility	0.73×10^{-11} Pa^{-1}
Hardness	45 - 55 DPH
Density	8.96 gcm^{-3}

Copper met the required adaptability of the test material to the chewing surface only in the thin-foil range. As the thickness increased (above approx. 50 µm), the foils proved to be too rigid.

5.3.2. Experimental setup for the foil tests

The tactile sensitivity of 73 participants who had taken part in Experiment 1 (assessment of tactile sensitivity using test objects in yogurt) was also tested using copper foil. Thirty-seven participants were male and 36 were female. The age distribution of the group is shown in Table 10.

The dental examinations conducted prior to the actual start of the test also included an assessment of the location of existing restorations (see Table 11).

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[12] Goodfellow Metals Ltd., Milton Road, Cambridge, England

Before the start of the experiment, we again provided the participants with a handout describing the experimental procedure. Here, too, we subsequently emphasized the key points once more and addressed any remaining questions.

Age group (years)	Number of participants
10 - 19	4
20 - 29	35
30 - 29	23
40 - 49	7
50 - 59	4

Table 10

Age distribution of the participants of the foil tests.

Dental treatment	Front teeth	Canines	Premolars	Molars
Total	71	65	70	71
Untreated	55	54	24	8
Fillings	12	8	8	20
One crown/ inlay/ onlay per tooth pair	4	2	16	5
One bridge pontic per pair of teeth	--	1	1	1
Two crowns/ inlays/ onlays per tooth pair	--	--	15	21
Two bridge pontics per pair of teeth	--	--	--	2
Fillings / crowns	--	--	2	4
Fillings / bridge pontics	--	--	--	1
Crowns / bridge pontics	--	--	4	9

Table 11

Dental condition of antagonistic anterior and canine teeth, premolars and molars.

The participants sat in a comfortable position in the dental chair. “White” and “pink” noise was transmitted from the cassette tape recorder through the headphones via a mixing console[13] at the highest possible volume. The examiner was able to give instructions to the subject via a microphone[14] connected to the mixing console and the headphones (see Fig. 3). The tests began in the anterior region. To this end, the patient practiced assuming an incisal-to-incisal position (edge-to-edge bite) several times. We then marked the opposing contact surfaces in this position using a double layer of marking tape[15]. Whenever possible, the test was performed between the incisor pairs 11/41 or 21/31 (see Fig. 4).

Handout describing the procedure of the experiment for the participants

> **"Test Procedure:** Tactile sensitivity of four different antagonistic tooth pairs
> The aim of the study is to determine the minimum thickness of a foreign object that can still be detected by the teeth. To this end, narrow copper foils of varying thicknesses are held between opposing tooth pairs using tweezers. It is necessary to mark the teeth beforehand with colored foil.
> Since foreign objects between the teeth can not only be felt but also heard to a considerable extent via bone conduction, hearing must be blocked during the test by playing white noise through headphones. At the same time, the ears are well sealed. We give the test subjects instructions regarding the test procedure (mouth “open” or “closed”) via the headphones. The eyes should be closed. After “close,” the test subject should decide whether a foil is definitely felt between the teeth.
> The teeth should not perform any rubbing motions, but only “open-close” movements against each other. The result of the decision should be communicated to the examiner without moving the head, by briefly pressing a button using a hand switch. As soon as the result is determined, the mouth should be opened slightly so that a new test can take place.
> The test is repeated 15 times, as each foil is tested a total of 15 times per pair of teeth. The foil will not always be between the teeth during this process. There may well be test series in which no samples are between the teeth.
> To prevent the foils from being felt against the oral mucosa or the tongue, the examiner holds the cheek to the side with an instrument during the test. The tongue must also not touch the foil during the test. Otherwise, the respective test must be repeated."

---

[13] Vivanco Model 9750

[14] Senator Electret Condenser Ribbon Microphone No. 381.541

[15] Hanel foil, Gebr. Hanel Medizinal, Nürtingen; single layer, 8 µm thick

Fig. 3

Test setup for determining tactile sensitivity using copper foils.

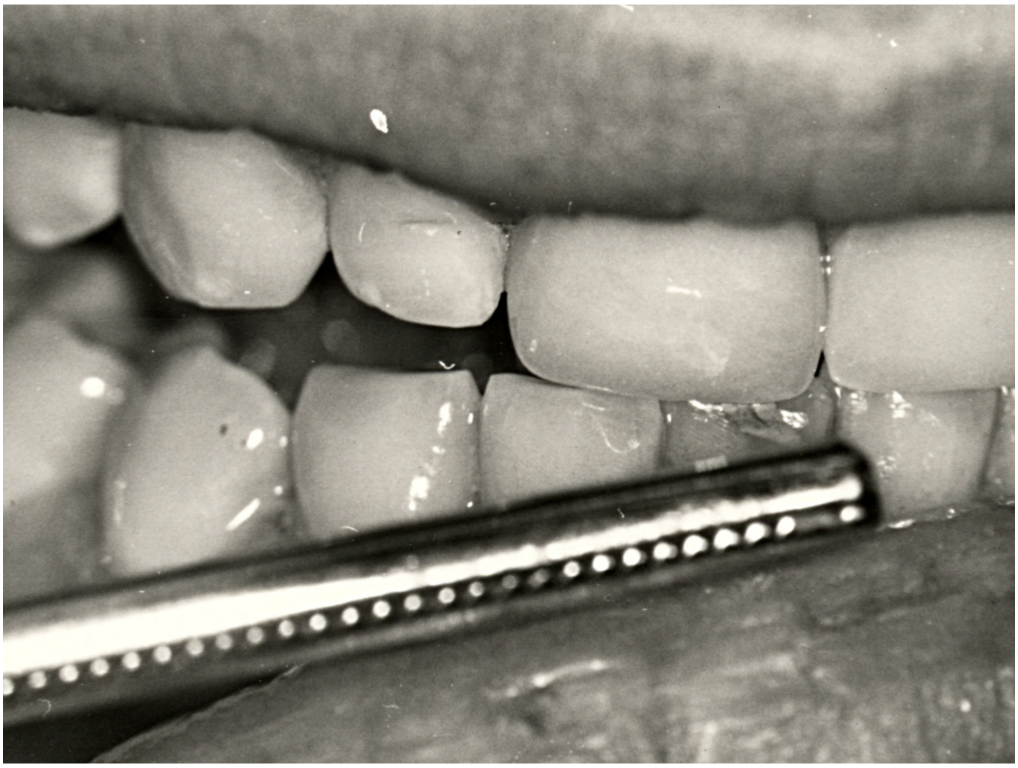

Fig. 4

Test setup for determining tactile sensitivity in the frontal region.

If this was not possible due to the occlusal conditions, the incisor pairs 12/42 or 22/32 were used instead.

In practice, we proceeded as follows: A piece of copper foil measuring approximately 2 × 15 mm was held firmly against the test tooth in the upper jaw using forceps, while the patient kept their mouth slightly open and their eyes closed. We attempted to prevent any feedback from contact with the tongue, lips, or cheeks through observation and instruction, as well as by using mouth mirrors or cheek retractors.

Upon hearing the command “close,” the subject moved the lower jaw into the practiced head-bite position. If they believed they could feel a foil between their teeth, they pressed the button on a handheld switch. This was connected to an electronic counter (see Fig. 5). If the subject did not feel a foil, they opened their mouth again so that a new test could begin.

Fig. 5

Selfmade electronic counter[16] with foot and hand switches

Using a foot switch, the examiner could enter and read the respective test number for a specific foil thickness into the counter without interrupting the test. The electronic circuit

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[16] Developer: Dr. Ulrich Wegmann, Poliklinik für Zahnärztliche Prothetik, Bonn

counted fifteen tests in this manner and randomly interspersed five “blank values” among them. The device thus indicated which test number corresponded to a foil being present between the teeth and which did not. If the test subject reported feeling a foil during a “blank test,” this was noted separately by the counter.

We always began the tests with the thickest foil and tested each foil thickness ten times in descending order; in addition, five blank tests were conducted. The test foils were available in thicknesses of 500, 250, 150, 125, 100, 75, 68, 50, 40, 34, 25, 20, 15, 10, 7, 6, and 3 µm. After testing a given thickness, we recorded how often the test subject had detected it among the ten actual foil samples and how often they reported a positive tactile sensation during blank trials.

The test series on a pair of opposing teeth was concluded when the subject was no longer able to detect a foreign object or when the thinnest foil (3 µm) had been detected. The individual foils were replaced with new ones whenever “bite marks” became visible that no longer ensured a consistent thickness.

After testing the front teeth, the canines were tested. They were examined in the same manner in the edge-to-edge position (see Fig. 6). In contrast, we tested premolars (see Fig. 7) and molars in the maximum intercuspation position of the lower jaw. In these cases, the test foil was adapted to the occlusal surface relief by closing the dental arch before the test began. For the posterior teeth, the foils were held between the occlusal surfaces in such a way that contact with the tongue or cheek was prevented. In most cases, only teeth on the right side of the jaw were tested. Only when the contact conditions on the right side did not allow for testing did we have to switch to the left side. We tested a total of 72 pairs of front teeth, 66 pairs of canines, 71 pairs of premolars, and 72 pairs of molars.

The entire experiment required extraordinary concentration from the participants. At the end of the approximately two-hour experiment, we asked the following questions:

1. Did you also feel the test foils with your mucous membranes, lips, or tongue?
2. Did you hear the contact with the test foils via bone conduction, or did you only feel the foil between your teeth?
3. Did you experience a metallic taste or galvanic currents in your mouth?
4. Did you feel the foil bending when you touched it?

The answers provide insights into possible methodological errors.

Fig. 6

Testing the canine teeth.

Fig. 7

Testing the premolars.

5.3.3. Criticism of the experimental setup

It is difficult to find ideal test specimens for the tests conducted. The challenges involved in material selection were discussed in Section 5.3.1.

The test results may have been influenced not only by the material but also by the tester; for example, foil strips held unsteadily may cause premature contact stimuli.

Some subjects tended to rub the contact surfaces or foils instead of performing vertical palpation movements. In such cases, it is the surface texture of the foil rather than its thickness that is being assessed.

Furthermore, the bite pressure during the palpation process and the dynamics of the movements could not be standardized.

A few subjects reported after the test that they had occasionally felt galvanic currents or a metallic taste.

The use of headphones, mouth mirrors, or cheek retractors, as well as the long duration of the experiment (approx. two hours), may also have affected the results due to a decline in concentration. Because of the long duration, only one test per person was possible. We were therefore unable to directly measure diurnal fluctuations in tactile sensitivity.

It is not possible to objectively determine whether bone conduction to the inner ear was completely blocked by the noise.

The tactile process of the posterior teeth differed from that of the anterior and canine teeth in both mandibular position and contact conditions, due to the experimental setup.

Depending on the type of occlusion and tooth position, the premolars and molars were excluded during the examination of the anterior and canine teeth. In the posterior region, the participants may have unconsciously utilized additional tooth contacts beyond the test teeth when using thin foils. A change in mandibular position during a test with a foil compared to a “blank test” is also conceivable.

6. Statistical Analysis

All results were analyzed using punch cards on the computer at the Regional University Computer Center in Bonn[17]. The methods used to calculate the results and the tests applied to compare the individual results are listed below (83, 128, 141, 153).

6.1 Calculations and tests using the results from Experiment 1 (Determination of tactile sensitivity using test specimens in yogurt)

- Calculation of the mean absolute tactile sensitivity of all participants based on the median value.
- Relationship between mean absolute tactile sensitivity and gender: Mann-Whitney U-test for two independent samples of ordinal data.
- Relationship between mean absolute tactile sensitivity and age (age groups: 10–19, 20–29, 30–39, 40–49, 50–61 years):
  - a) One-way Kruskal–Wallis rank-sum analysis (H-test) for multiple independent samples of ordinal-level data.
  - b) Mann–Whitney U-test to compare the mean absolute tactile sensitivity of the individual age groups with one another.
- Dependence of the mean absolute tactile sensitivity between the centric condylar position and the maximal intercuspal position (0–0.5; 0.6–1; 1.1–2.5 mm): H-test.
- Dependence of the mean absolute tactile sensitivity on the type of tooth guidance:
  - a) Mann-Whitney U-test for the groups: canine protected articulation and group canine/group guidance.
  - b) t-test for the groups: canine protected articulation and group canine guidance and group guidance.
  - c) U-test to compare the mean absolute tactile sensitivity among the individual occlusal guidance groups.
- Dependence of the mean absolute palpation ability on the circadian rhythm (examination times: 8–11 a.m., 11 a.m.–2 p.m., 2–6 p.m.):
  Friedman's two-way rank-sum test for multiple dependent samples for ordinal-level data.

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[17] The software used to generate all the calculations was developed by Dr Dipl Math Konrad Oettershagen, Institute of Physiology at the University of Bonn. We owe him our heartfelt acknowledgements for his prompt and clear assistance, as well as for his guidance on statistical issues, without which such a comprehensive analysis would not have been possible!

- Dependence of the mean absolute tactile sensitivity on training effects; testing of tactile sensitivity on different days while accounting for a possible diurnal rhythm: Wilcoxon signed-rank test for two dependent samples with ordinal-level data.

6. 2. Calculations and tests using the results from Experiment 2 (Determination of contact sensitivity using metal foils)

6.2.1. Tests of average absolute tactile sensitivity

- Calculation of the mean absolute tactile sensitivity of the incisors, canines, premolars, and molars for all participants based on the median value.
- Dependence of the mean absolute tactile sensitivity of all tooth types on gender: U-test
- Dependence of the mean absolute tactile sensitivity of all tooth types on age (age groups: 10–19, 20–29, 30–39, 40–49, 50–61 years):
    - a) H-test to determine whether the mean absolute tactile sensitivity of all tooth types in the age groups originates from the same population
    - b) U-test to compare the mean absolute tactile sensitivity of all tooth types across the individual age groups
- Dependence of the mean absolute tactile sensitivity of all tooth types on the extent of the sliding movement between the centric condylar position and the maximal intercuspal position (0–0.5; 0.6–1; 1.1–2.5 mm): H-test
- Dependence of the mean absolute tactile sensitivity of all tooth types on the type of tooth guidance (examination times: 8–11 a.m., 11 a.m.–2 p.m., 2–6 p.m.)
    - a) U-Test for the groups: canine and group-canine and group occlusion
    - b) H-Test for the groups: canine and group-canine and group occlusion
- Dependence of the mean absolute tactile sensitivity of all tooth types on the state of dental restoration:
    - a) H-Test for the various forms of dental restoration (temporary/resin/amalgam fillings - inlays/onlays/crowns - bridge pontics)
    - b) U-test for comparing untreated and treated teeth
- Dependence of the mean absolute tactile sensitivity of all tooth types on the circadian rhythm (examination times: 8–11 a.m., 11 a.m.–2 p.m., 2–6 p.m.)
    - a) U-test to compare tactile sensitivity across the individual time groups
    - b) H-test to compare tactile sensitivity among all time groups
- Comparison of the mean absolute tactile sensitivity among the individual tooth groups: U-test

6.2.2. Tests for the 50% sensitivity[18]

- Calculation of the ‘initial’ 50% sensitivity [19]of the incisors, canines, premolars, and molars of all participants based on the median value[20]
- Calculation of the “interpolated” 50% sensitivity of the incisors, canines, premolars, and molars for all participants based on the median value.
- Relationship between the 50% sensitivity of all tooth types and gender: U-test
- Dependence of the 50% sensitivity of all tooth types on the sliding movement between the centric condylar position and the maximal intercuspal position: H-Test
- Dependence of the 50% sensitivity of all tooth types on age groups: H-Test
- Dependence of the 50% sensitivity of all tooth types on the type of occlusal guidance: U-test for the groups: canine and group canine/group guidance
- Dependence of the 50% sensitivity of all tooth types on the state of dental restoration: H-test for the various forms of dental restoration
- Dependence of the 50% sensitivity of the individual tooth groups on one another
  - a) Wilcoxon
  - b) U-test

6.2.3. Correlation between mean absolute tactile sensitivity and 50% sensitivity

Spearman's rank correlation coefficient as a nonparametric measure of correlation for ordinal-level data.

6. 3. Comparison of the data from Experiment 1 and Experiment 2

- Correlation between the mean absolute tactile sensitivity in Experiment 1 and the mean absolute tactile sensitivity of all tooth types at the same times of day: Rank correlation coefficient
- Differences between the mean absolute tactile sensitivity in Experiment 1 and the mean absolute tactile sensitivity of all tooth types at the same times of day: Wilcoxon test
- Comparison of the mean absolute tactile sensitivity of the anterior and posterior teeth

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[18] The 50% sensitivity indicates the film thickness at which a participant reports positive sensations in 50% of the 10 test trials (see Section 5.3.2) and negative sensations in the other 50% of cases.

[19] Since this 50% threshold could be crossed multiple times due to the physiological range of variation (see Figs. 14 and 18), we calculated the value in two ways. First, the film thickness was determined as the 50% sensitivity at which the participants crossed the 50% threshold for the first time (“first” 50% sensitivity). Second, the first reading before the first crossing of the 50% threshold and the first reading after the last crossing were taken. The corresponding film thickness was then interpolated between these two values.

[20] In the calculation, the blank tests incorrectly reported as ‘positive’ by the participants were subtracted from the values that were actually positive for this film thickness.

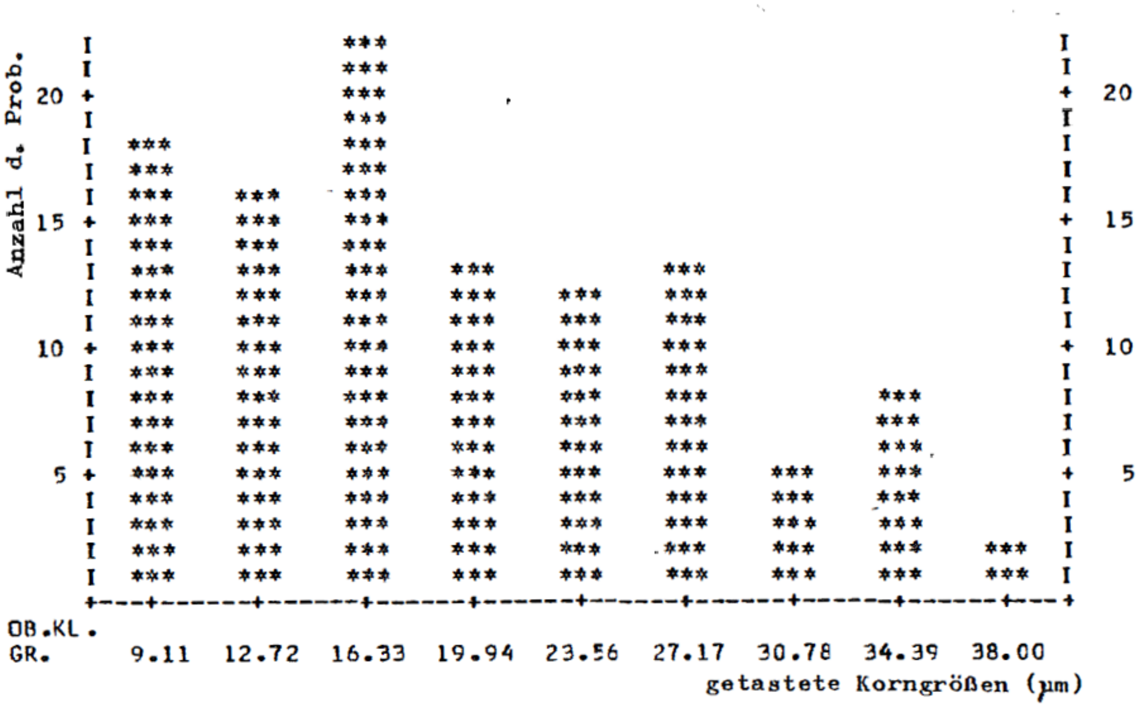
from Experiment 1 with the mean absolute tactile sensitivity of the anterior and posterior teeth from Experiment 2: Chi-square test (four-field table)

7. Results from Experiment 1 (Testing tactile sensitivity using aluminium oxide particles in yogurt)

We conducted 297 experiments and a total of approximately 5,000 individual tests on 109 participants. Forty-eight participants from the group were tested on a single day in the morning, at noon, and in the late afternoon. We tested another 24 participants multiple times on different days at the same times of day. We tested all the remaining participants only twice in one day or up to seven times at different times on different days.

In the survey following the experiment, the participants reported 32 times that they had felt the foreign bodies mainly with their front teeth, 150 times only with their side teeth, and 115 times with both their front and side teeth.

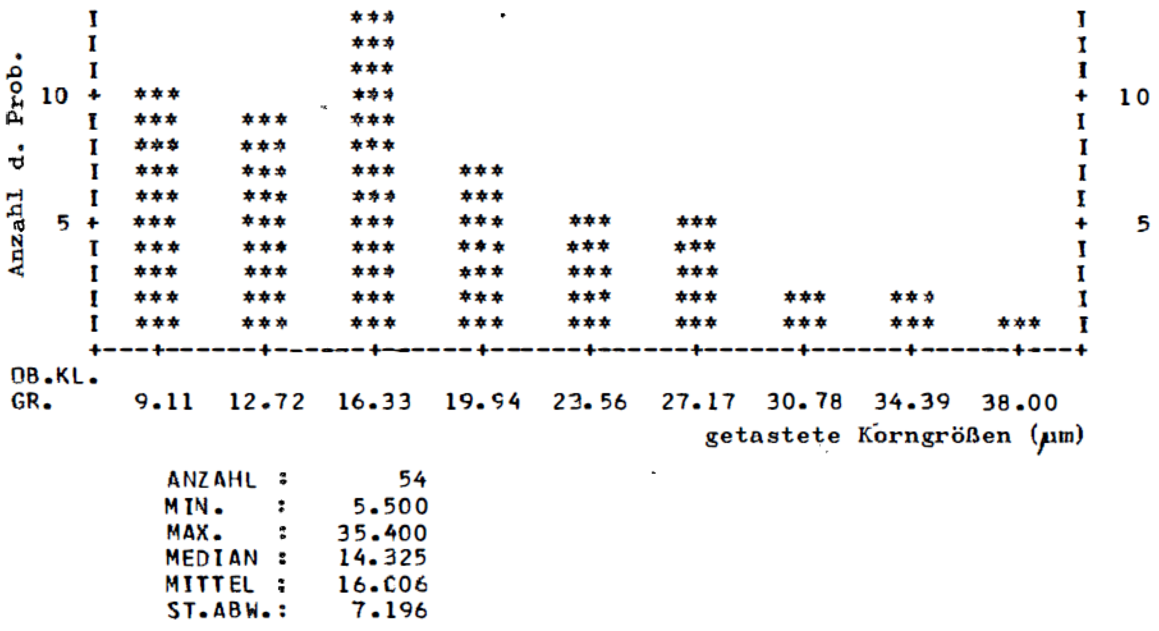
The smallest aluminium oxide particles detected in the yogurt by the individual test subjects ranged in size from 5.5 µm to 38 µm. This yields a median value of 15.2 µm (see Fig. 8).



```
ANZAHL  :      109
MIN.    :    5.500
MAX.    :   38.000
MEDIAN  :   15.200
MITTEL  :   17.359
ST.ABW. :    7.796
```

Fig. 8

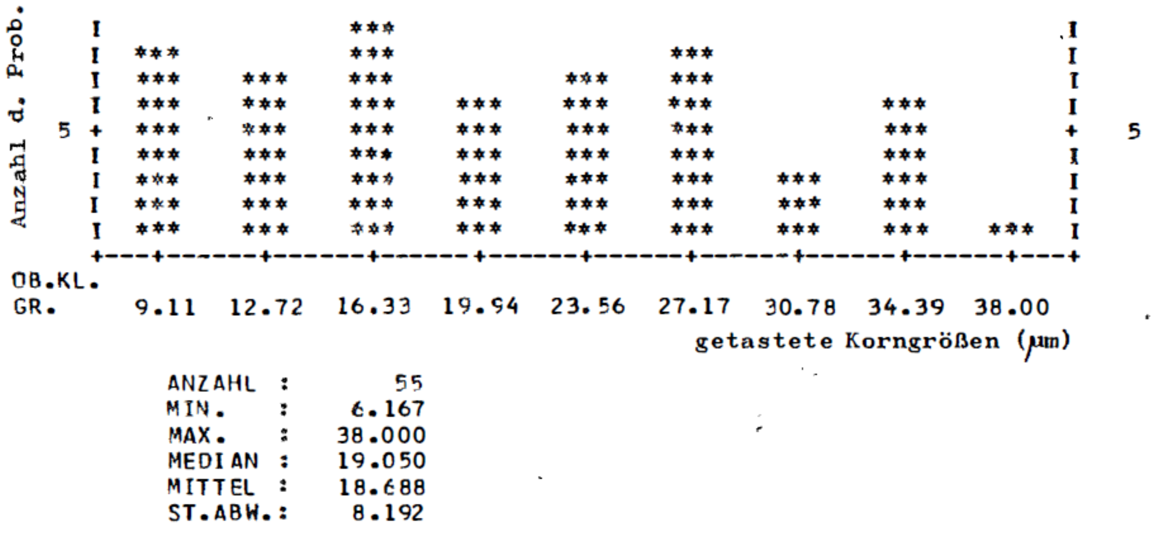
Distribution of the mean values of the Al_2O_3 grain sizes still detectable by touch among the group of subjects



```
ANZAHL :      54
MIN.   :   5.500
MAX.   :  35.400
MEDIAN :  14.325
MITTEL :  16.006
ST.ABW.:   7.196
```

Fig. 9

Distribution of the mean values of the Al_2O_3 grain sizes still detectable by touch and their distribution in male subjects.



```
ANZAHL :      55
MIN.   :   6.167
MAX.   :  38.000
MEDIAN :  19.050
MITTEL :  18.688
ST.ABW.:   8.192
```

Fig. 10

Distribution of the mean values of the Al_2O_3 grain sizes still detectable by touch and their distribution in female subjects.

The median value for the female test participants (19.1 µm) was significantly higher than that of the male test subjects (14.3 µm; see Figs. 9 and 10).

The participants continuously refined their tactile sensitivity over the course of a day (see Table 12). From this, one might conclude that tactile ability changes according to a biorhythm. However, the results can also be explained by practice effects (see Section 10.1). We therefore conducted a retest, assuming that the first test for each subject was not influenced by training effects. Since the test series began at different times of day for some subjects, we compared these corresponding results. However, we were unable to statistically demonstrate a diurnal fluctuation in tactile sensitivity.

We were interested in whether tactile ability remains stable over a longer period of time. To this end, we compared the mean values of 24 subjects at the same times of day on days as far apart as possible. We hoped this would minimize any potential training effects. The resulting mean values are shown in Table 13.

Time of day		
8-11	**11-14**	**14-18**
18.7	15.8	12.9

Tab. 12: Time-of-day variation in tactile sensitivity (Significance Level: 1%).

Aluminium Oxide Grain Tests	**1. Test**	**2. Test**
Mean values of absolute sensitivity (µm)	18.8	14.4

Tab. 13

Changes in task capacity on various days.

We assume that the minimum tactile sensitivity cannot fall below a certain threshold. However, this implies that any potential training effects should be particularly evident in a participant’s initial tests. We therefore also compared the last two tests for each participant, which were conducted at the same time of day. Statistically, no difference could be detected between the corresponding mean values. The improvement in tactile sensitivity over time that was initially observed is therefore likely due to practice.

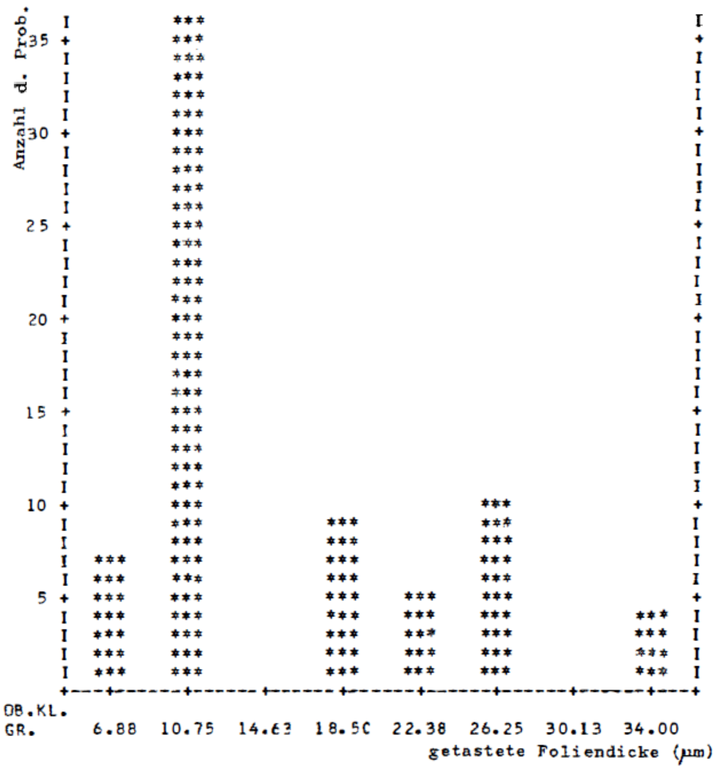
We were unable to identify any statistical correlations between minimal tactile sensitivity and age, occlusal guidance, or the magnitude of the sliding movement between the centric condylar position and the maximal intercuspal position.

8. Results from Experiment 2 (Assessment of tactile sensitivity using copper foils between opposing tooth pairs)

We examined 277 opposing tooth pairs in 73 participants who also took part in Experiment 1. This required approximately 66,500 individual tests.

8.1. Tactile sensitivity of the front teeth

The thinnest foils detected by individual test subjects between their front teeth during the test had a thickness ranging from 3 to 34 µm, with a median value of 10.0 µm (see Fig. 11).



```
ANZAHL :       71
MIN.   :    3.000
MAX.   :   34.000
MEDIAN :   10.000
MITTEL :   13.335
ST.ABW.:    8.422
```

Fig. 11

Distribution of the mean values of the copper foils just touched between the anterior teeth in the group of subjects

No statistical correlation of the mean values with gender, age, time of day, type of dental restorations, or the magnitude of the sliding movement between the centric occlusion (CO) and the maximal intercuspal position (MIP) could be demonstrated. In contrast, tactile sensitivity was lower for participants with a canine protected articulation (9 µm ± 2.8 µm) than for those with a group-canine protected articulation (16 µm ± 9.7 µm; significance = 5%, see Table 14).

Foil tests	**Front teeth**			**Canine teeth**			**Premolars**			**Molars**		
	Canine protected articulation	**Group guidance**	**Group-canine protected**	**Canine protected articulation**	**Group guidance**	**Group-canine protected**	**Canine protected articulation**	**Group guidance**	**Group-canine protected**	**Canine protected articulation**	**Group guidance**	**Group-canine protected**
Absolute threshold	8	10	15	15	20	34	8	10	15	9	10	15
Significance	5%			<5%			5%			---		
50% threshold	18	31		50	64		21	17		15	16	
Significance	<5%			---			---			---		

Tab. 14

Tactile sensitivity as a function of dental alignment (Median values in µm, rounded)

Calculation of the 50% sensitivity[21] of the anterior teeth yielded values between 1.5 µm and 253.8 µm with a median of 28.6 µm (see Figs. 12 and 13). An example of an individual test is shown in Fig. 14.

---

[21] The calculation of the ‘initial’ 50% sensitivity resulted in test values that were, in some cases, significantly lower than those obtained using the “interpolated” 50% sensitivity. Since, with one exception, all statistical tests (conducted using both values of the ‘first’ 50% sensitivity and values of the ‘interpolated’ 50% sensitivity) yielded no qualitative differences in the results for the parameters we examined, we will publish below the values of the interpolated 50% sensitivity, which has also been used in the existing literature. We specifically highlight results corresponding to the ‘first’ 50% sensitivity. However, we note that the definition of the 50% threshold can lead to significantly different values. Overall, we prefer the ‘interpolated’ 50% sensitivity, as it yields statistically more reliable values.

Participants with canine protected articulation also recorded lower values (17.8 pm ± 7.911 m) than those with group or group-canine protected articulation (33.3 µm ± 22.4 µm; see Table 14). No correlation was found between 50% sensitivity and gender, age, time of day, type of dental restoration, or the magnitude of the sliding movement between the centric occlusion and maximal intercuspal occlusion.

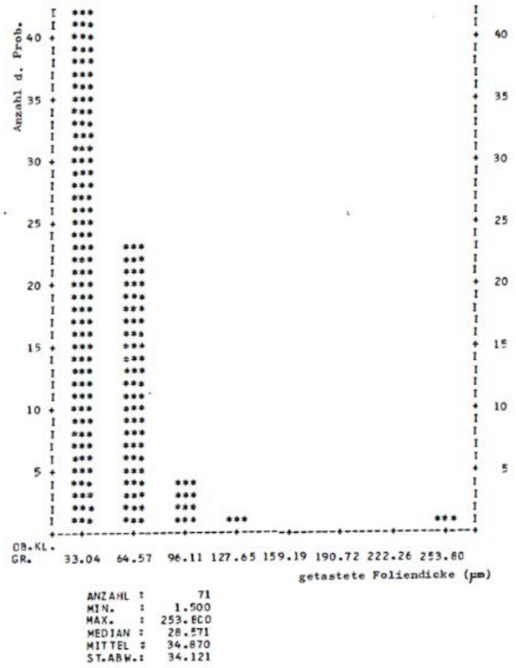


Fig. 12

Distribution of the mean values of the 50%-sensibility of the anterior teeth in the study population.

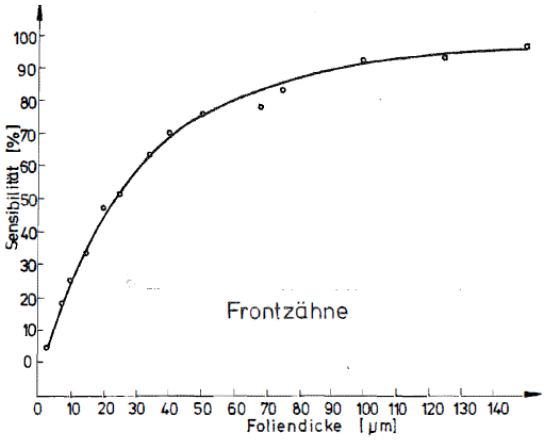


Fig. 13

The average %-sensitivity of the anterior teeth in the study population.

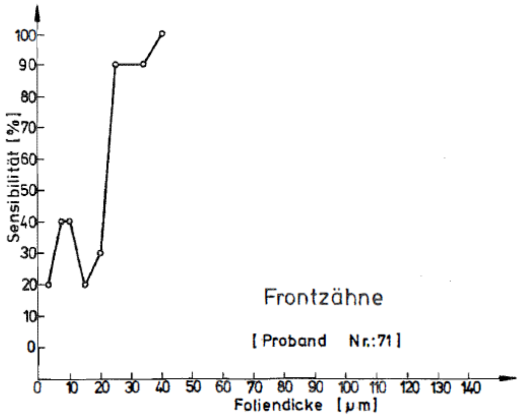


Fig. 14

%-sensitivity of the anterior teeth of participant No. 71

8.2. Tactile sensitivity of the canines

The thickness of the thinnest foils detected between the canines ranged from 3 µm to 150 µm, with a median value of 20.0 µm (see Fig. 15). We were unable to demonstrate any influence of gender, age, time of day, or the sliding motion between the centric occlusion and maximal intercuspal occlusion. However, participants with a canine protected articulation achieved better readings (median 15 µm) than those with a group-guided bite (median 20 µm) or a group-canine protected articulation (median 34 µm; see Table 14).

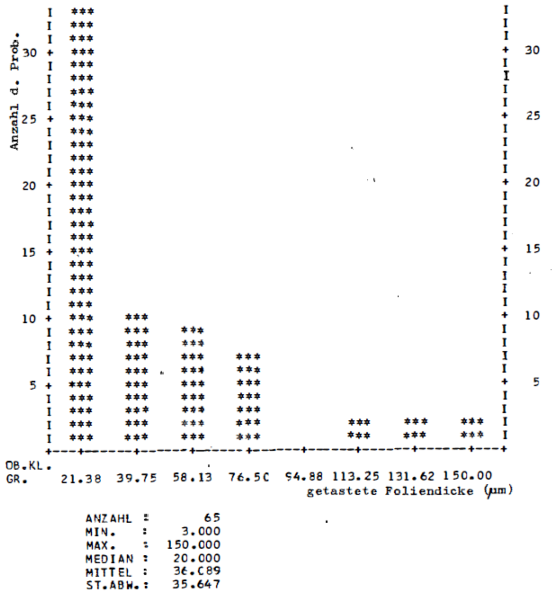
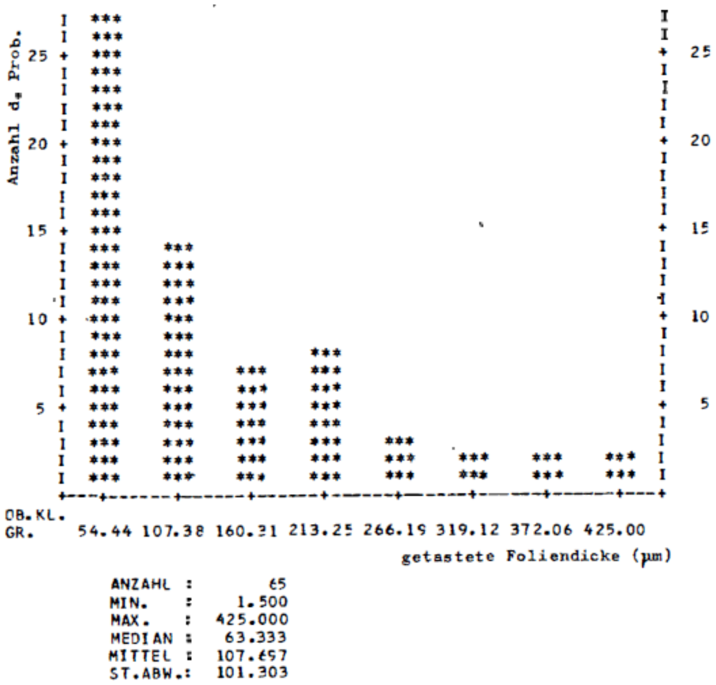


Fig. 15

Distribution of the mean values of the copper foils just still detectable between the canine teeth in the group of subjects.

The 50% sensitivity of the canines ranged from 1.5 µm to 425 µm, with a median of 63.3 µm (see Figs. 16 and 17). Fig. 18 shows the individual test results for participant No. 66. In this case, we were unable to statistically confirm the other potential influencing factors we had considered.



```
ANZAHL :        65
MIN.   :     1.500
MAX.   :   425.000
MEDIAN :    63.333
MITTEL :   107.657
ST.ABW.:   101.303
```

Fig. 16

Distribution of the mean values of the 50%-sensitivity of the canines in the group of subjects.

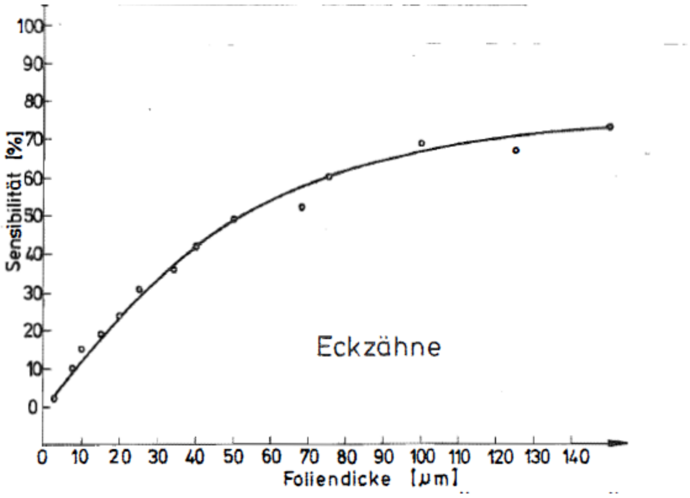


Fig. 17

The average %-sensitivity of the canines in the study population.

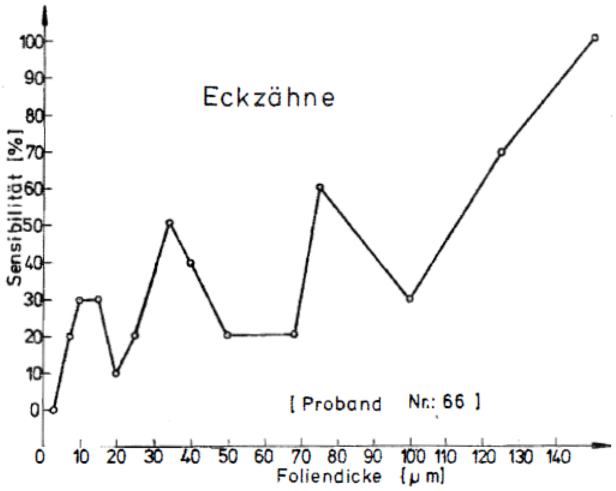


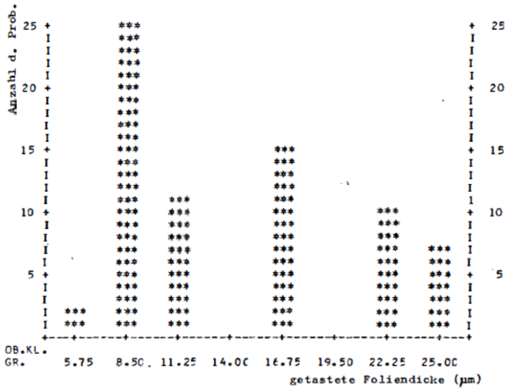
Fig. 18

%-sensitivity of the canines of participant No. 66

8.3. Tactile sensitivity of the premolars

The premolar test revealed that the thinnest foils were those ranging from 3 µm to 25 µm. The median value was 10.0 µm (see Fig. 19).

We were unable to demonstrate that the values were affected by gender, age, time of day, or sliding motion between centric occlusion and maximal intercuspal occlusion. At the limit of statistical significance, there was a dependence of tactile sensation on a canine protected articulation (10.4 µm ± 6.8 µm) or a group canine protected articulation (14.2 µm ± 5.9 µm; see Table 14).

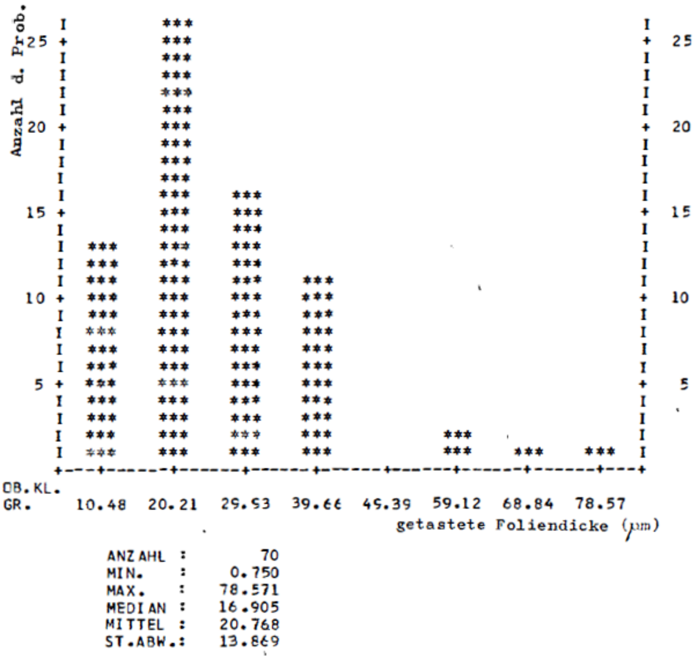


```
ANZAHL :        70
MIN.   :     3.000
MAX.   :    25.000
MEDIAN :    10.000
MITTEL :    12.543
ST.ABW.:     6.122
```

Fig. 19

Distribution of the mean values of the copper foils touched by the premolars in the study cohort.

The 50% sensitivity ranges from 0.8 p-m to 78.6 µm and has a median of 16.9 µm (see Figs. 20 and 21). None of the potential influencing factors considered in the study led to a statistically significant change in the measured values.



```
ANZAHL  :       70
MIN.    :    0.750
MAX.    :   78.571
MEDIAN  :   16.905
MITTEL  :   20.768
ST.ABW.:    13.869
```

Fig. 20

Distribution of the mean values of the 50%-sensitivity of the premolars in the study population.

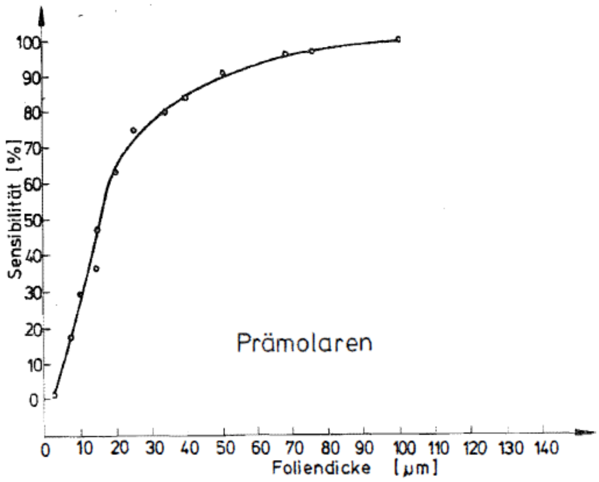


Fig. 21

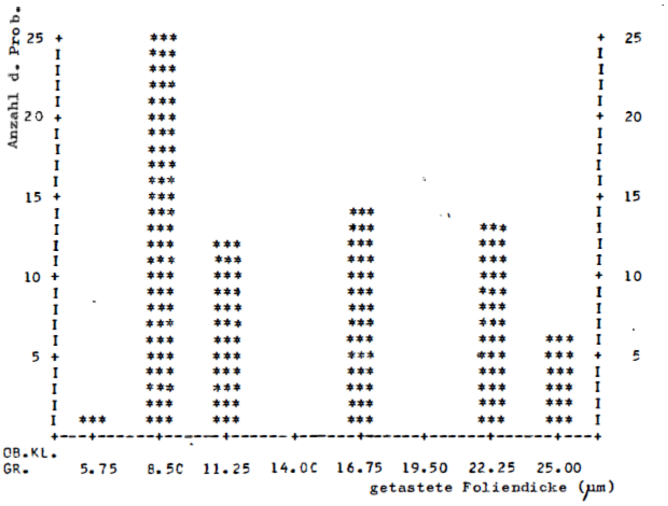
The average %-sensitivity of the premolars in the study population.

8.4. Tactile sensitivity of the molars

The thickness of the thinnest foils—those touched by the participants—ranged from 3 µm to 25 µm. The median value was 10 µm (see Fig. 22).

The 50% sensitivity ranged from 5.3 µm to 100 µm, with a median value of 16.5 µm (see Figs. 23 and 24). An example of an individual test is shown in Fig. 25, which depicts the test sequence for participant No. 105.

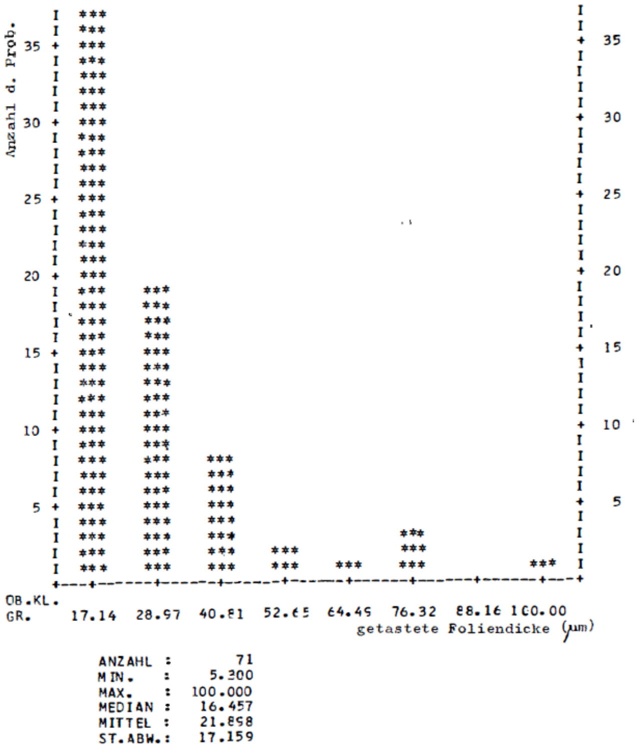
The influence of gender, age, time of day, the sliding movement between maximal intercuspal occlusion and centric occlusion, and the type of tooth guidance could not be statistically demonstrated for either the “thinnest foils” or the 50% sensitivity.



```
ANZAHL  :      71
MIN.    :   3.000
MAX.    :  25.C00
MEDIAN  :  10.000
MITTEL  :  13.141
ST.ABW.:    5.967
```

Fig. 22

Distribution of the mean values of the copper foils just still detectable between the molars in the sample



```
ANZAHL :        71
MIN.   :     5.300
MAX.   :   100.000
MEDIAN :    16.457
MITTEL :    21.858
ST.ABW.:    17.159
```

Fig. 23

Distribution of the mean values of the 50%-sensitivity of the molar teeth in the study population.

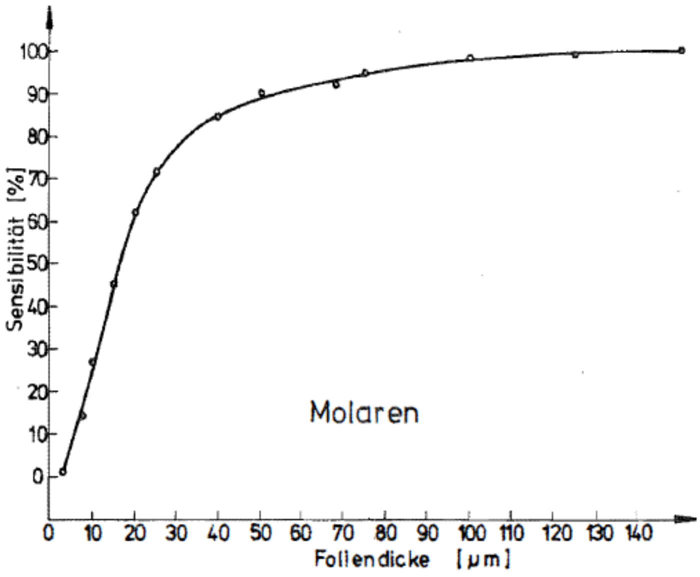


Fig. 24

Average %-sensitivity of the molars in the sample.

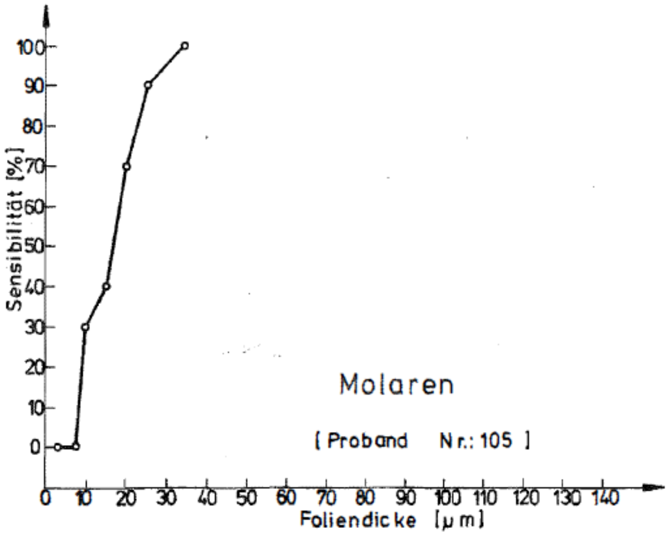


Fig. 25

%-sensitivity of the molars of participant No. 105.

8.5. Comparison of the tactile sensations of the front teeth, canines, premolars, and molars

To compare the tactile sensitivity of the incisors, canines, premolars and molars, we first examined the mean values for all participants regarding the thinnest foils that could just about be detected (= absolute tactile threshold). The tactile sensitivity of the canines was significantly lower (significance level 1%) than that of all other types of teeth (see Table 15).

Foil tests		**Front-teeth**	**Canines**	**Premolars**	**Molars**
Absolute sensitivity	Range	3-34	3-150	3-25	3-25
	Mean ± SD	13 ± 8	36 ± 36	13 ± 6	13 ± 6
	Median	10	20	10	10
"first" 50%-sensitivity[22]	Range	1-73	2-375	1-64	5-71
	Mean ± SD	22 ± 16	62 ± 72	17 ± 11	20 ± 15
	Median	18	38	14	15
"interpolated" 50%-sensitivity	Range	2-254	2-425	1-79	5-500
	Mean ± SD	35 ± 34	108 ± 101	21 ± 14	22 ± 17
	Median	29	63	17	17

Tab. 15

Comparison of the tactile sensitivity of individual tooth groups (values rounded).

---

[22] These results have been adjusted to remove outliers

We carried out the Wilcoxon test based on the ‘interpolated’ 50 per cent sensitivity. We were unable to detect any differences in tactile sensitivity between the premolars and molars in individual subjects. However, the tactile sensitivity of the incisors and canines differs highly significantly (1‰) from that of the premolars and molars (see Table 15, Fig. 26); the significant differences in tactile sensitivity also apply to the comparison between incisors and canines.

We used the U-test to compare the values for the ‘first’ 50% sensitivity of the individual tooth groups. The anterior teeth, premolars and molars differed highly significantly (1‰) from the canines. The difference between the anterior and posterior teeth was no longer detectable (see Table 15).

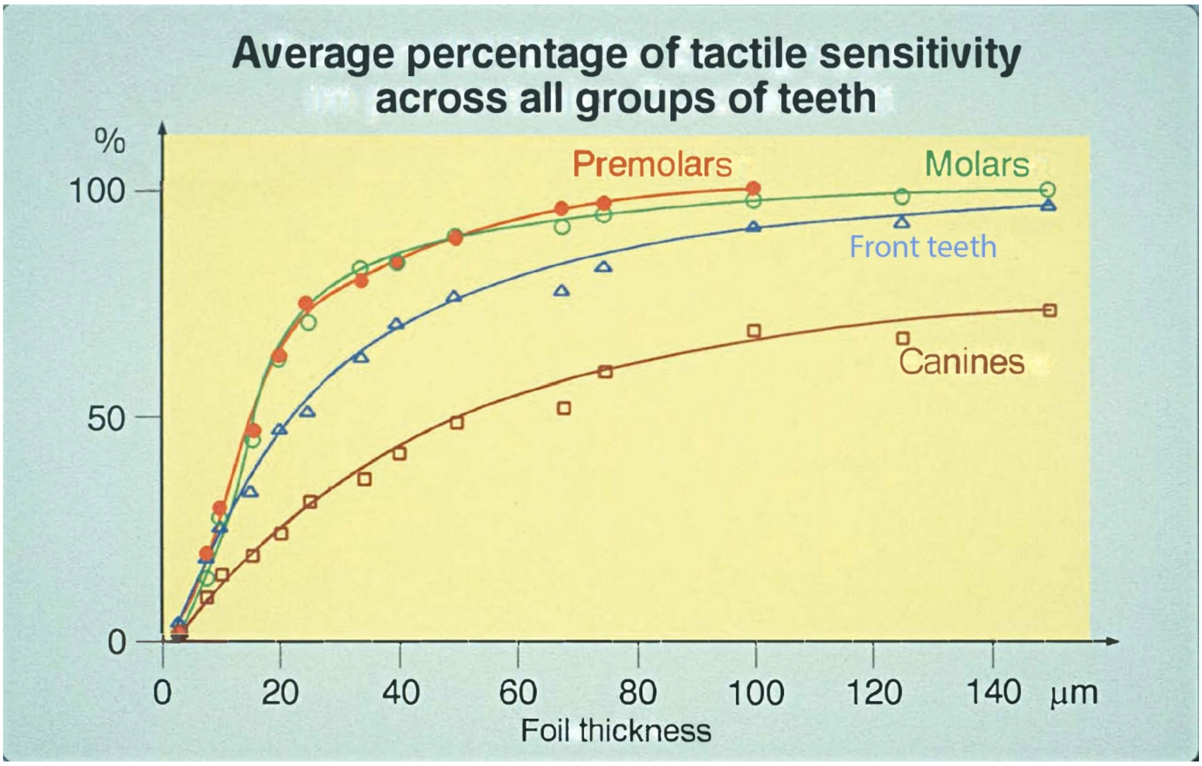


Fig. 26

Average %-sensitivity of the anterior teeth, canines, premolars and molars in the study population.

8.6. Analysis of the Correlation Between Absolute Tactile Ability and 50% Sensitivity

To determine whether there was a correlation between the thinnest film thickness of a particular tooth type that participants could just about detect by touch and the corresponding 50 per cent sensitivity, we used the rank correlation coefficient. This revealed a very clear statistical relationship between the two values (see Table 16). We therefore carried out most of the tests using only the mean values of absolute tactile sensitivity.

Foil tests	Front teeth	Canines	Premolars	Molars
Number of subjects	71	65	70	71
Correlation coefficient	0.65	0.66	0.71	0,79
Significance	< 1%	< 1%	< 1%	< 1%

Tab. 16

Correlation between absolute tactile ability and 50% sensitivity based on the data of experiment 2.

8.7 Comparison of the tactile sensitivity of teeth that have undergone dental treatment and those that have not

To investigate the influence of dental restorations on tactile sensitivity, we compared treated teeth with untreated teeth. The treated teeth included: teeth with temporary and permanent fillings, cast restorations, crowns and bridge pontics. The differences between the mean values for absolute tactile sensitivity of treated and untreated anterior teeth and molars were statistically significant (5%). The untreated anterior teeth and molars thus exhibited greater tactile sensitivity. In contrast, tactile sensitivity was the same for both treated and untreated canines and premolars (see Table 17).

Foil tests	Front teeth		Canines		Premolars		Molars	
	No.	**Median**	**No.**	**Median**	**No.**	**Median**	**No.**	**Median**
Untreated teeth	55	10 µm	54	25 µm	24	10 µm	8	7,7 µm
Treated teeth	15	20 µm	11	15 µm	40	10 µm	49	10 µm
Significance	< 5%		---		---		< 5%	

Tab. 17

Comparison of absolute tactile sensation (median values) in dentally treated and untreated teeth.

9. Comparison of the Results from Experiments 1 and 2 (Absolute Tactile Sensitivity for Aluminium Oxide Grains and Copper Foils)

We applied various statistical tests to compare the results between Trials 1 and 2. In each case, we compared all the tactile results from Trial 1 (aluminium oxide) with those for the individual tooth types from Trial 2 (copper foils) (see Table 18). Our initial aim was to determine whether a participant with very fine tactile sensitivity in Experiment 1 (i.e. a low measured value) would also demonstrate this in Experiment 2 (again, a low measured value). Using the rank correlation coefficient, we were only able to establish a correlation between the tactile sensitivity results from Experiment 1 and those for the anterior teeth in Experiment 2 (see Table 19).

On the one hand, the overall results of Trials 1 and 2 are numerically close to one another; on the other hand, a statistical correlation in the absolute tactile sensitivities is evident only for the front teeth. We therefore used the Wilcoxon test to investigate whether the values obtained for individual participants in Trials 1 and 2 were consistent. Statistically, the values from Trial 1 can only be matched with those for the front teeth and molars from Trial 2 (see Table 20).

Furthermore, we calculated whether a participant who had mainly detected the aluminium oxide particles in Experiment 1 using their posterior teeth (or anterior teeth) also exhibited the highest sensitivity in Experiment 2 using their premolars (or anterior teeth). The four-way chi-square test revealed no statistical correlations.

Comparison of Experiment 1 with 2		Sensitivity in µm			
		Front teeth	Canines	Premolars	Molars
Aluminium grains	**Range**	6-38			
	Mean ± SD	17±8			
	Median	15			
Copper foils	**Range**	3-34	3-150	3-25	3-25
	Mean ± SD	14±8	36±36	13±6	13±6
	Median	10	20	10	10

Tab. 18

Comparison of the results from experiments 1 and 2 (values rounded)

Correlations in tactile sensitivity between Experiments 1 and 2	Front teeth	Canines	Premolars	Molars
Number of participants	63	58	61	62
Correlation coefficient	0,21	0,14	0,08	0,12
Significance	< 5%	---	---	---

Tab. 19

Correlation of the results from experiments 1 and 2 (as tactile sensitivities of the individual participants)

Comparison of Experiment 1 with 2	Front teeth	Canines	Premolars	Molars
Number of participants	63	58	61	62
Significance of the comparison	---	< 1%	< 5%	---

Tab. 20

Difference in the numerical values of the results from Experiments 1 and 2 for individual participants.

10. Discussion

10.1. Testing tactile sensitivity using aluminium oxide in yoghurt

We have already discussed sources of error attributable to the initial experimental setup in Section 5.2.4.

To the best of our knowledge, comparable studies have so far only been carried out by MANLY et al. (105), as well as by ÖWALL (119, 120) and ÖWALL et al. (121). MANLY et al. (105) mixed various quantities of calcium carbonate into custard. The test subjects had to determine the proportion of calcium carbonate at which they first noticed a change in the custard's texture. Dentate participants could already detect an addition of 2.9% calcium carbonate, whereas participants without teeth could only detect it from 9% calcium carbonate in the carrier medium. In this test, therefore, similar to our preliminary experiments, proportions were determined, but particle size (approx. 12.5 µm) was not taken into account. ÖWALL (120) mixed steel balls of varying sizes with a test food (popcorn, cheese, peanuts). The test subjects were asked to identify, whilst chewing, the smallest steel ball they could just about detect. He found that the 50% sensitivity lay between 560 µm and 650 ± 100 µm. According to these studies, the structure of the food has little influence on the results, whereas the size of the bolus has a significant effect.

According to studies by HANNAM et al. (52), it is the contact between the teeth and the food bolus that primarily influences the normal chewing pattern, rather than the resistance of the food itself.

Our results, with a median value of 15 µm (mean 17 µm ± 8 µm), are very much lower than those of ÖWALL. Due to the design of the first series of experiments, our median value corresponds to the 'absolute' detection threshold of our participants; a 50% sensitivity based on test specimens of varying thicknesses cannot be calculated.

The significant discrepancy in the results could, on the one hand, be attributed to differences in the structure of the carrier media (popcorn, cheese, peanuts+, yoghurt) and the test specimens (steel balls / aluminium oxide), and, on the other hand, to the different chewing patterns observed (52, 120). To break down peanuts, one is likely to use habitual chewing cycles. Yoghurt, on the other hand, tends to encourage rubbing movements. It can be assumed that the participants in the ÖWALL test (steel ball test) closed their teeth slightly more cautiously, as people are reluctant to bite into very hard objects in their food.

Gender differences

The results for the female participants in our study (19 µm) differ from those of the male participants (14 µm). However, other authors have been unable to demonstrate gender differences in tactile ability – albeit in different studies (14, 155). Only WILLIAMS et al. (177) also found that the results for male participants were lower – though not statistically significant.

Diurnal rhythm

One of the many factors influencing the results is the biological rhythm (109). Many functions of the human organism exhibit a wide range of rhythms with very different frequencies (from 1/1000 of a second up to years; (61)). The diurnal fluctuation in performance must therefore be taken into account as a influencing factor (165). Physical performance peaks at three o'clock in the morning (64). 'Physical working capacity' then declines fairly steadily until the following evening, before reaching its peak once more. However, the daily pattern of mental performance runs in the opposite direction to the 'physiological performance curve' (64). Moreover, not everyone has the same rhythm; there are 'morning' and 'evening' types (165).

Initially, our participants' scores improved very steadily from around 19 µm in the morning to 13 µm in the late afternoon. Unfortunately, due to the design of our experiment, we were unable to distinguish a biorhythm from the training effects. We therefore compared the first tests for each participant, which we categorised by time of day. No diurnal variation in the results could be detected. This may, of course, also be due to the fact that individual differences are greater than the influence of a circadian rhythm.

Tests carried out on the same participants on different days, far apart in time, at the same times (including the first test) showed an improvement in the result of approximately 3 µm. By contrast, when we compared the last two tests of a participant on different days at the same times, the results were statistically identical.

Certainly, we can only conclude from our results that training effects occur particularly at the start of a series of tests. A refinement in tactile sensitivity over the course of the day is possible, but would need to be verified by a modified experimental design.

MANGELS (104) and PÖLLMANN (131) observed, in their experiments, that tactile sensitivity peaked in the evening, whereas HOLLSTEIN (67) suggests that participants' results may deteriorate in the evening due to fatigue. STEWART (164) reports higher pressure thresholds in the afternoon compared with the evening. However, the studies listed did not take training effects into account.

Age

In our investigations, we found no evidence that increasing age influences the results. This is consistent with the findings of the foil tests conducted by SIIRILÄ et al. (156). In the study by ÖWALL (120), however, older participants achieved better results than younger ones. SKRAMLIK (158) found a higher touch threshold in older people than in younger ones. Age-related differences were also observed by LITVAK et al. (100) in oral spatial perception, and by BRILL et al. (14) in two-point discrimination 1) of the skin in the trigeminal region.

Tooth guidance

Whilst preparing our experiments, the idea arose that the nature of the antagonistic tooth contacts in different mandibular positions might influence tactile sensitivity during mastication; depending on which contacts the participants use during the test, it is conceivable that varying numbers and sizes of tooth surfaces might come into contact. We reasoned that, among participants with group guidance, the masticatory movement might habitually tend to have a lateral component. Consequently, the teeth would then also be subjected to a greater horizontal component of force. MANLY et al. (105) observed a lower lateral contact threshold compared with the axial contact threshold for the anterior and posterior teeth. By contrast, forces of varying intensity – whether applied axially or horizontally to the anterior and canine teeth – can be detected equally well (8, 9). However, in their electrophysiological studies, KIZIOR et al. (82) found even more action potentials under axial tooth loading than under lateral tooth loading.

ADLER (1), HANNAM (50, 51), JERGE (72), JOHANSSON et al. (74), KAWAMURA (78), KAWAMURA et al. (79), NESS (116) and PEASLEE (125) have demonstrated that the periodontium of the teeth is, in principle, highly capable of distinguishing between stimuli from different directions. Our study was unable to demonstrate any effect of tooth guidance or the magnitude of the sliding movement between the retral contact position and the maximal intercuspal position on tactile sensitivity. According to GRAF et al. (42, 43), most tooth contacts during the masticatory cycle occur in the maximal intercuspal position; PAMEIJER et al. (123) also found only isolated contacts in the centric condylar position. According to SCHAERER et al. (142), the very brief eccentric tooth contacts that occur during mastication serve primarily to guide the mandible into the maximal intercuspal position. Our results are consistent with these observations.

10.2. Testing tactile sensitivity using copper foils between opposing pairs of teeth

Possible sources of error in the experimental setup were already highlighted in Section 5.3.3. Studies on tactile sensitivity using wires or foils placed between opposing teeth have already been carried out on several occasions (16, 67, 87, 88, 108, 155, 168, 170; see Table 2).

50% sensitivity

The seminal work defining the so-called ‘50% sensitivity’ of teeth was carried out by TRYDE et al. (170). The authors base their approach on the idea that tactile sensitivity does not cease abruptly at the perception threshold when using a thin foil. If this foil is tested repeatedly between opposing teeth, the participants will feel it on one occasion but will not necessarily perceive it the next time. If one then tests increasingly thinner foils, the subject will, from a certain threshold onwards, no longer be able to detect a foreign body between the teeth. In this way, a 50% sensitivity can be calculated at the end of the experiment. If a foil at the S_{50} threshold is tested, for example, 10 times, it will therefore be detected five times and not detected five times. This 50 per cent threshold will generally be higher than the ‘absolute’ tactile threshold, as in extreme cases the ‘absolute’ tactile threshold in our study is a 10 per cent sensitivity.

Absolute tactile sensitivity and 50% sensitivity

Our median values for absolute tactile sensitivity are 10 µm for the incisors, premolars and molars, and 20 µm for the canines. As explained above, the median values for 50% sensitivity are higher, namely 29 µm for the anterior teeth, 63 µm for the canines and 17 µm for the premolars and molars (see Table 15). Our values are broadly consistent with the results described in more recent literature (see Table 2). To date, no foils below 8 µm have been tested in the literature; nor have any attempts been made to eliminate bone conduction. HOLLSTEIN (67) is the only author to have published results on absolute tactile sensitivity for all types of teeth. He found the lowest values for the incisors. For the premolars and molars, the tactile threshold was higher. We are unable to confirm this.
To our surprise, the participants were able to palpate most reliably using their premolars and molars. This is reflected both in a low absolute threshold and a low S_{50} value. The result is consistent with the statements made by the participants in Experiment 1, where many of them reported having detected the aluminium oxide grains using their posterior teeth.

Tactile sensitivity of the different types of teeth

Although the absolute tactile threshold of the anterior teeth is identical to that of the premolars and molars, their 50 per cent threshold is higher. This contradicts the findings of SIIRILÄ et al. (155), who observed – albeit not significantly – greater sensitivity in the anterior teeth compared with the posterior teeth. The canine shows significantly poorer results than the other tooth types, both for the absolute tactile threshold and, in particular, for the s50 value (see Table 15 and Fig. 26). It cannot be ruled out that this is related to the different tactile positions of the lower jaw during the test with the anterior teeth, as opposed to those with the posterior teeth. Depending on the degree of mouth opening, different receptor systems may be responsible for the perception of foreign bodies of varying thicknesses (see Chapter 4.6, Table 4, p. 21). Very thin foils allow contact between adjacent molars. It is conceivable that perception occurs via the differing magnitudes of movement of these teeth within the alveolus compared with the test teeth. □YAMADA (178), who carried out electrophysiological studies on dogs in 1967, found that tooth movement of 2–3 µm can trigger action potentials in the associated nerve units. A movement of 10 µm in a single tooth resulted in clear stimulus responses. In terms of magnitude, our findings are entirely consistent with these results. SIEBERT (152) noted that, when the dental arch closes, movements of between 5 and 10 µm occur in the lingual and distal directions. No information is provided regarding the extent of the axial movement involved.

However, in the case of antagonistic incisors and canines – which, when in the incisal-edge-to-incisal-edge position, often have no other contacts with neighbouring teeth – such a palpation mode is unlikely. In these cases, the periodontium alone cannot convey the difference in thickness. Receptors in the temporomandibular joint or in the masticatory muscles could be a possibility.

The difference in tactile sensitivity between the front teeth and canines also remains striking. For both types of tooth, the degree of mouth opening during the test was certainly roughly the same, even though the examination of the canines additionally required a lateral displacement of the lower jaw. We are currently unable to provide a conclusive explanation for this reduced sensitivity of the canines. We believe that this cannot be explained either by the size of the root and the differing pressure loads required to trigger a sensory response, nor by a genetically determined reduction in the innervation of the periodontium of the canines. On the contrary, the canines of animals – which are, admittedly, larger than human canines – occupy the largest projection area in terms of surface area of all tooth types in the nucleus principalis and nucleus spinalis of the trigeminal nerve in the brain (79, 92).

In our investigations, we found no clear difference between the tactile sensitivity of participants with a molar-dominated occlusion and those with a canine protected articulation (see below). However, during the experiment, we did not individually evaluate the adjacent tooth contacts in the incisal edge-to-incisal edge position of either the anterior teeth or the canines for each participant.

Gender

In line with SIIRILÄ et al. (155), we were unable to detect any differences between the absolute tactile thresholds of male and female participants. In 1947, ADLER (1) investigated the maximum stimulation threshold and reported lower values in girls. Following an investigation into two-point discrimination of the skin, BRILL et al. (14) found no gender differences. Similarly, WILLIAMS et al. (177) found that gender had no influence on the values when differentiating between test objects of varying thicknesses placed between the front teeth.

Age

In our investigations into the tactile sensitivity of all groups of teeth, we were unable to detect any age-related differences – as was also the case with SIIRILÄ et al. (156) in tests involving the front teeth. However, our age groups were not evenly distributed. ÖWALL (120), on the other hand, reports an improvement in tactile sensitivity with increasing age.

Time of day

H0LLSTEIN (67), MANGELS (104) and PÖLLMANN et al. (131) found fluctuations in tactile perception over the course of the day. These findings could not be confirmed by our experimental design, in which the tactile test results of various participants were examined.

Dental restorations

When we examined the individual restorative materials in groups (see Section 7.2.1.), we were unable to demonstrate any difference in tooth sensitivity. However, when we compared all teeth that had undergone dental treatment with those that had not, the tactile sensitivity scores for the treated anterior teeth and molars were worse (see Table 17). In the case of the canines and premolars, the differences could not be statistically confirmed. We are currently unable to provide a satisfactory explanation for this result.

SKRAMLIK (158) reports that conservative treatment of a tooth has no effect on pressure sensitivity. In contrast, GNEUPEL-GREIZ (41), H0LLSTEIN (67) and L0EWENSTEIN et al. (101) found that tactile sensitivity was less pronounced with fixed prostheses. Various authors have demonstrated that teeth with a root filling have the same tactile sensitivity as those with vital pulp (7, 41, 60, 61, 67, 99, 116, 126, 168). Only SKRAMLIK (158) reports a “profound change” in pressure sensation in root-filled teeth.

There were too few root-filled teeth among our participants for us to take this factor into account. However, we believe that the receptors responsible for tactile sensation in the teeth are located in the periodontium and not in the pulp (see also Chapter 4 and the following discussion).

Tooth guidance

We were able to statistically confirm that absolute tactile sensitivity depends on the type of occlusal guidance during eccentric mandibular movements for the anterior teeth, canines and premolars (see Table 14). Participants with anterior/canine guidance exhibited a more refined tactile sensitivity in these teeth than those with group or group-canine protected articulation. However, the results for 50% sensitivity do not confirm this finding – with the exception of the front teeth. For this reason – and because we were only able to examine eleven participants with immediate canine protected articulation – we view this correlation with great scepticism and do not wish to attach any significance to it.

10.3. Comparison between Experiments 1 and 2

The statistical tests for the absolute tactile threshold yielded results that were broadly consistent across both experiments (see Table 18). However, from a statistical point of view, the values for the individual participants in Experiment 1 can only be matched with their front teeth and molars from Experiment 2. High measured values in Experiment 1 correlate only with similarly high measured values for the front teeth in Experiment 2. However, both findings imply that the two investigative methods cannot simply be interchanged. The two methods assess different levels of tactile sensitivity. This may be due to the chewing and rubbing movements carried out in Experiment 1 (‘dynamic tactile threshold’, STEENBERGHE (162)), which, compared to the chopping movements of Experiment 2 (‘active’ tactile threshold, STEENBERGHE (162)), may be embedded in a more complex reflex process. The teeth may have been set into slight vibration, for example, by the roughness of the aluminium oxide abrasive particles. However, the method of testing absolute tactile sensitivity using aluminium oxide grains in yoghurt—presented here for the first time—offers the advantage of being able to test a large number of participants. Each individual test takes at most a quarter of the time required for foil tests. The level of the sensory wave value can be determined quite accurately, and the natural masticatory cycle is not disrupted by external influences.

At the end of the test, none of the participants reported having felt the grains in the yoghurt with their tongue. We might cautiously conclude from this that dental sensitivity to foreign bodies is, in some respects, even greater than the generally recognised high sensitivity of the tongue.

11. Summary

The tactile sensitivity of natural teeth was measured in two series of experiments. First, we determined the absolute tactile threshold using a yoghurt-based food in which approximately 0.3 per cent by weight of aluminium oxide grains were evenly distributed. The threshold was 15 µm (median value), with male participants able to detect slightly smaller foreign bodies than female participants. In multiple tests on the same participant, the threshold could be influenced by training effects, but could not be reduced at will.

In the second series of experiments, we investigated the tactile sensitivity of dentate participants using copper foils. The absolute tactile threshold yielded the following values: incisors, premolars and molars 10 µm; canines 20 µm.

Calculation of the 50% sensitivity yielded 29 µm for the incisors, 63 µm for the canines and 17 µm for both the premolars and molars. No gender-related or circadian fluctuations in tactile sensitivity could be detected. The significantly lower sensitivity of the canines compared with the other types of teeth requires further attention in future tests.

In both experiments, no statistically significant correlation was found between the participants' tactile sensitivity and their age, occlusion, the gliding movement between the centric condylar position and the maximal intercuspal position, or the dental restorations on their teeth.

The two sets of experiments tested different levels of tactile sensitivity and are therefore not interchangeable. From a practical perspective, the results imply that dentists must pay close attention to the occlusal equilibration of dental restorations.

12. Bibliography

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I was born in Solingen on 20 October 1950, the son of Karl Utz, and his wife Ingeborg (née Baudler).

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In October 1971, I enrolled at the Friedrich-Wilhelms-Universität in Bonn, initially to study biology and, from April 1972, dentistry.

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