Clin Oral Invest (2004) 8:130–138
DOI 10.1007/s00784-004-0267-2

ORIGINAL ARTICLE

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In vivo validation of the historical in vitro thermocycling temperature range for dental materials testing

Received: 2 February 2004 / Accepted: 28 April 2004 / Published online: 23 June 2004

Abstract In dental research, restorative materials have been regularly subjected to alternating in vitro thermal stress in investigations since the 1950s, in order to simulate in vivo alternating temperature stress and to artificially stress them in vitro. The provocation temperature is mostly 5°C for cold provocation, and 55°C for hot provocation. These temperatures are determined quite arbitrarily based on very few examinations in vivo. Extensive temperature data for the approximal space of teeth, which is decisive for the success of fillings adhesively attached to dentin, has so far not been addressed. The objective of this study was to examine the interproximal temperature characteristics created in the space of all teeth in vivo with thermal alternating stress, and therefore to validate the in vitro standardized thermal alternating stress of 5–55°C. Fifteen study participants with healthy teeth were used to determine the temperature in each interdental space, resulting from hot/cold provocation in the upper and lower jaw, from the central incisor to the second molars. This was performed by a thermal element (cable sensor GTF 300, Greisinger Electronic GmbH, Regenstauf, Germany). The temperature sensor was attached with dental floss into the interproximal space and the temperature was recorded by the computer. The participants in the pilot test had to state when they were able to sip an 85°C hot drink. That particular temperature value was taken for hot provocation as maximum temperature reference. Cold ice water (0°C) was used for cold provocation as minimum temperature reference. The respective recordings with a total of 14 measurements for each individual were performed simultaneously in the upper and lower jaw. The study participants were to start with hot provocation, followed by cold provocation. This cycle was repeated at least once with an individual dwell time. The highest recorded approximal space temperature was 52.8°C in the lower jaw, between the first and the second premolar. The lowest temperature of 13.7°C was recorded in two participants in the upper jaw, between the 1st and 2nd incisor, and between the two central incisors. The mean of the maximum temperatures was 43.8±3.7°C, and the mean of the minimum temperatures 24.2±4.6°C. The mean initial temperature was 35.2±1.3°C. None of the recordings reached either the upper threshold (55°C) or the lower threshold (5°C). This study showed that the actual thermal stress in the interproximal space of teeth is slightly lower than the one used in in vitro examinations. For class II cavities, most of the alternating temperature stress limits selected at 5–55°C cover the actually occurring temperature interval quite well.

Keywords Adhesive dentistry · In vivo · Thermocycling · Validation

Introduction

Teeth are subject to significant temperature changes during intake of food of various temperatures. Hot drinks are served at up to 85°C, and ice cream as low as −12°C. Food is therefore eaten within a temperature span of 80–90°C [15]. The temperatures recorded in the dental enamel show a drop of 16°C with cold foods, and an increase to 48°C with hot foods and drinks [15, 28]. These temperature differences create various modifications to the hard tooth structure due to the different thermal expansion of enamel and dentin [14]. Temperature changes in one tooth cause thermal stress, which is proportional to the temperature difference the tooth experiences. With sufficient repeated high or low thermal stress, the tooth structure may be damaged [3, 8]. The sensitivity test with dry ice can lead to cracks in the enamel or enlarge enamel defects already present [3].

Dental enamel consists of 93–98 pct. by wt. of inorganic material, between 1.5 and 4 pct. by wt. of water, as well as inorganic compounds such as proteins and lipids.

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Dentin, however, consists of 70 pct. by wt. of inorganic, and 20 pct. by wt. organic material. The remaining substance is water [17]. The linear coefficient of dental enamel (11.4 ppm/°C) and dentin (7.5 ppm/°C) are known [3, 14, 45]. Gente et al. in their research illustrated and recorded the deformation of enamel-dentin strips similar to a bimetallic strip, in a "pain-free" temperature zone from 26 to 48°C [13, 14]. They also transferred the results of their examination to a cavity model, and thus showed the consequences on marginal adaptation of in vitro restorations. Roydhouse et al. made similar observations with regard to cavity dimensions in their research of class V cavities in vitro [39]. With each temperature change in the oral cavity, hard tooth structure tissue and filling material contracts or expands in correlation with the thermal expansion coefficient. This differential dimensional effect not only influences the marginal fit, but also causes a liquid stream in the marginal gap [10].

The materials which are used today to adhere to the hard tooth structure must resist the surrounding influences in the oral cavity, including temperature changes [22]. In developing new restorative materials, special attention is paid to reducing the setting contraction, increasing the strength, and closely adapting the thermal volume effect to that of the hard tooth structure [10]. Nelsen et al. were the first to research the problem of dimension changes between filling and hard tooth structure in connection with temperature changes [31]. Studying cooled teeth with different restorations present in vitro by means of an optical microscope, they observed that from the interface between restoration and tooth, small liquid drops formed as the spot was warmed by hand [50]. This liquid stream of molecules or ions, clinically not noticeable, is known today under the term "micro-leakage" [22, 50]. Microleakages and therefore leaking restoration margins can lead to sensitivity and discoloration, as well as to secondary cavities through bacterial penetration, pulpitis or the loss of fillings [22]. The examination of restorative materials for thermal characteristics has, since Nelsen, developed into a generally acknowledged test procedure under the term "thermocycling" in dental research [21, 32, 33, 50].

In laboratory conditions, restored teeth are thermally alternately stressed, and their marginal quality/leakage is evaluated by dye penetration, scanning electron microscopy, radioactive isotopes, bacteria and even artificial caries [22, 23]. The thermal alternating stress is to simulate in vitro the actual in vivo occurring stress of the interface between hard tooth structure and restoration material. A large number of publications confirm a decrease of the marginal seal after thermocycling [9, 38, 41, 46].

The best-known method of intra-oral temperature recording is the determination of the sublingual temperature [40]. In one study, the temperature of the oral cavity of 50 healthy students was measured, which showed a mean of 36.2°C [5]. Numerous recordings deal with the sulcus temperature, the gingiva temperature relevant to their health status or the circadian rhythm [1, 2, 12, 20, 24, 29, 30, 49]. The effect of oral breathing on the teeth was also examined [6].

In order to examine thermal stress in the approximal space, it is essential to consider as many variables as possible which could influence the temperature of the teeth. The main sources equilibrating temperature in the mouth are cheek, tongue and the periodontal tissue surrounding the teeth [7, 19]. An external factor is breathing; however, this has only a slight effect, and mainly affects the front teeth of the upper jaw [6, 7, 11]. The main factor that leads to a temperature change is intake of food and beverages of various temperatures [15, 36].

Since the entire oral capacity functions like a heat exchanger, temperature peaks decay quickly, as can be seen in many temperature trends. There is, however, a latency period which is required by the oral capacity to reach its normal temperature again. For example, consuming ice cream over a certain period of time can result in short peaks and a drop of the oral temperature beyond the time it takes to consume the food. The original temperature will be restored only through circulation and breathing. An overview of the existing literature on in vivo temperature recordings is shown in Table 1.

Pfeifer et al. [36] observed that the intake temperature does not represent the temperature measured in the mouth. Rather, the temperature in the oral cavity depends on the temperature conductivity and heat capacity of the food consumed. Generally the higher the water content of food, the higher the heat capacity.

Several authors decided on hot drinks, as in this study (Table 1). Palmer et al. [34] determined by testing 13 people, that all consumed the hot drink at a temperature of above 61°C. Nelsen et al. [31] noticed a maximum incorporated temperature of 60°C in five participants. Several authors have conducted their tests with hot drinks at 60°C without noting whether this temperature was determined by a pilot test or not [35, 44].

Other authors report sensitivity by the participants, e.g., that the 70°C hot drink was "hard to take" [27], "comfortable" at 50–55°C, or "hot, but acceptable" at 55–60°C [37]. In the same study, six participants felt that drinks with a temperature above 68°C were too hot [37]. During the study by Youngson and Barclay, [50] the participants were offered coffee with a temperature of 72.5°C, which was sipped the first time after it stood for 1 min. Longman and Pearson [26] conducted the most extensive tests with 22 participants. They determined a drink temperature which was between 53–74°C. Most people preferred a temperature between 55–68°C.

In most of the examinations, with the exception of Palmer (13 study participants) [34], and Pfeifer (ten study participants) [36], only a very small group of people (1–4) was investigated. None of the authors took all teeth into account during testing.

The objective of this current study was to determine the temperature created in the interproximal space of all teeth in vivo of a larger number of participants under various temperature conditions. This research was to determine if the standardized temperature alternating stress

Table 1 Overview of the literature: temperature ranges of incorporated hot and cold food or beverages and measured maximum and minimum temperatures with related references

Author	Year	Temperature of hot food or beverage [°C]	Maximum oral temperature measured [°C]	Temperature of cold food or beverage [°C]	Minimum oral temperature measured [°C]
Nelsen [31]	1952	60	52	4	9
Gräf [15]	1960	69 (potato)	45	5	16
Peterson [35]	1966	60	45	0	15 (10)
Plant [37]	1974	63.5	53.5	-	-
		58	50		
		55	47		
Simmons [42]	1976	Hot coffee	49	Iced tea	4.4
Mesu [27]	1983	70 (solid)	60	−15 (ice cream)	0
		60 (solid)	50	−7 (ice cream)	8
		55 (solid)	48	10	24
Longman [26]	1986	65	50 (ca.)	0	13 (ca.)
Spierings [44]	1987	60	50.5	0	13.4
Pfeiffer [36]	1989	81 (Potato)	76	0 (ice cube)	3
				−8 (ice cream)	−2
Palmer [34]	1992	>61	58.5	0	1
Michailesco [28]	1995	69	48.4	5 (tomato salad)	18.9
				0 (ice cube)	4.3
Youngson [50]	2000	72.5	68.0	6.0	15.4

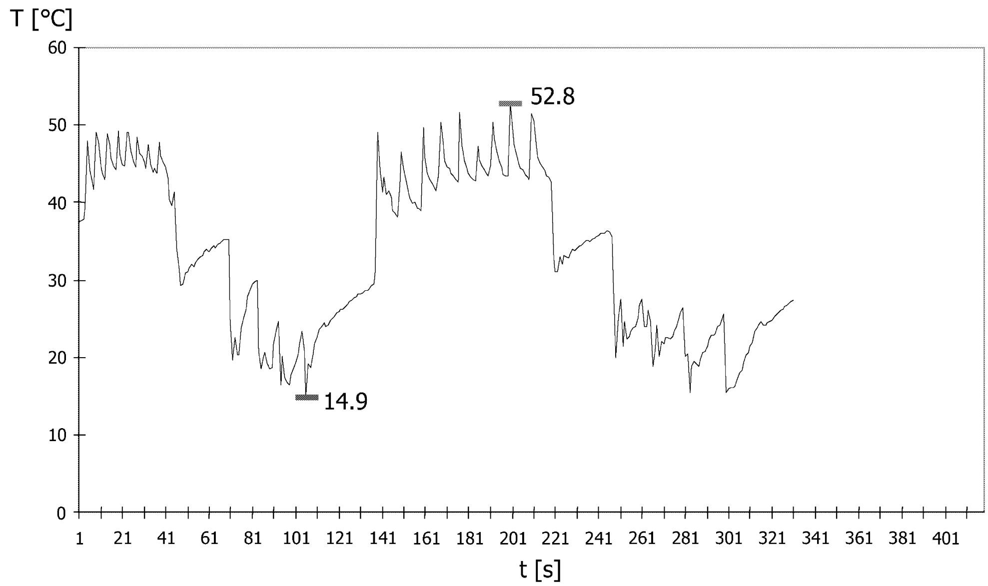


Fig. 1 Temperature recordings of participant D, as obtained from the testing spot 4-5 in the lower jaw

of 5–55°C, which is specified in many in vitro examinations, corresponds to the actual in vivo stress, or should be adjusted.

Materials and methods

Fifteen volunteers (11 women and four men) aged 18–28 years (mean: 22.2) were included in the study. One of the criteria for the study participants was that they had to have a full set of healthy teeth, no missing teeth (with the exception of the third molars), and a eugnathic dental arch in the upper and lower jaw, without a strong rotation and hinge. There must not be any fillings in the teeth that were to be measured, or any larger fillings anywhere else. The periodontium had to be healthy. There must be no bleeding when dental floss was applied in the approximal space. The interdental papilla had to fill out the interproximal space and there had to be no sign of infection. There must be no general or systematic diseases present.

The study participants themselves determined the drinking temperature. Tea in various flavors was selected as the hot drink. It was heated with a simple, small immersion heater (Prosper-Elektro-Apparatebau F. Rohm GmbH, Schalksmühle, Germany).

Fourteen tests were conducted on each participant, which consisted of seven measurements each in the upper and lower jaw. The respective recordings in the upper and lower jaw were performed at the same time. One temperature value was transferred per second. At the same time, a characteristic curve could be established from the individual temperature values on the computer (Figs. 1 and 2).

The temperature was controlled with a digital thermometer GTH 1150 (LCD-Digital-Sekunden-Thermometer, Greisinger Electronic GmbH, Regenstauf, Germany; Measuring range: −50°C to +1,150°C; resolution: 1°C; accuracy: −20°C to +550°C <1% ±1 digit) with the matching measuring sensor GTF 300 (cable sensor GTF 300, Greisinger Electronic GmbH, Regenstauf, Germany). Starting with a temperature of 85°C, the study participant was asked to sip the tea, which was transferred to a thermal mug with steel insulation (WMF Württembergische Metallwarenfabrik AG, Geislingen/Steige, Germany) and test the temperature carefully. If the participant was able to take several sips in a row and swallow them without scalding, this was the temperature which was

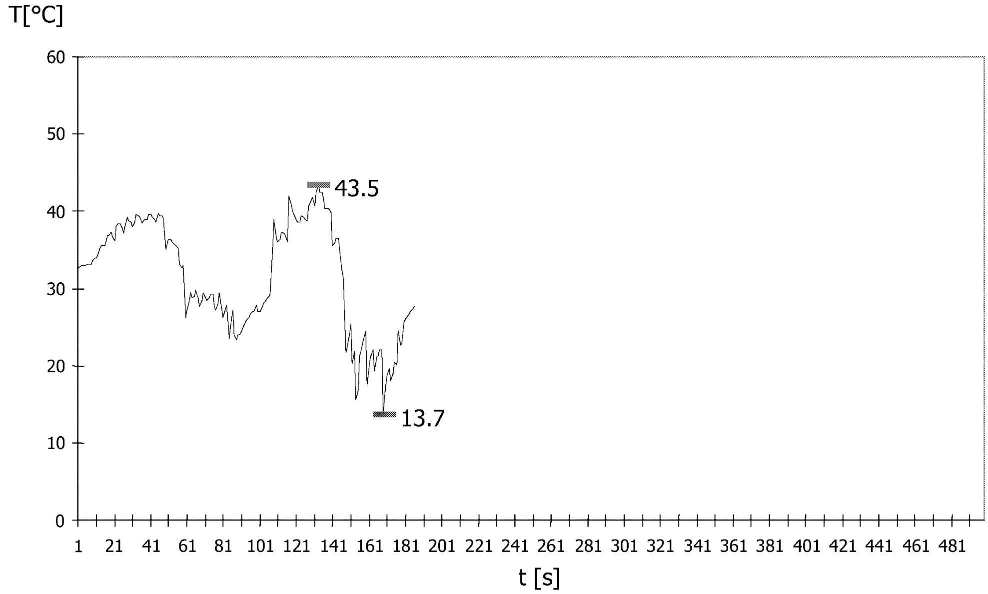


Fig. 2 Temperature recordings of participant F, as obtained from the testing spot 1-2 in the upper jaw

then recorded in the record. This was the temperature that was used as the upper reference point for the respective study participant. The tea was heated to this temperature and controlled before each participant sipped it.

The minimum reference temperature for cold stress was determined as 0°C, since this temperature approximately corresponds to the mean value of the minimum incorporated temperatures [15, 27, 28, 35, 36]. Water (Vittel, Nestlé Waters, Switzerland) with crushed ice was used as the medium. The advantage of ice water is the constant temperature of 0°C, which means that the reference temperature can easily be controlled and reproduced.

The probe used for the measurements in the oral area could not cause errors if saliva was present. In addition, the size of the thermal element was selected in such a way that it could be safely inserted and attached into the interproximal space without damaging the interdental papilla. An additional important requirement was a quick response time (about 1 s) in the measuring probe, since temperature peaks can occur within seconds, as well as sterilizability for clinical use.

The micro temperature measuring probe consisted of two Teflon-coated, spiral thermal-element wires of nickel/chrome-nickel with a diameter of 0.2 mm each, and a length of about 1 m, as well as a thermal de-energized miniature flat pin plug (1/2 DIN 43710). According to the manufacturer's data, this sensor is suitable for surface and depth measurements, and has a response time in liquids of 0.3 s. The measuring range for the sensor is from −65 to +300°C. Only the tips of the wire ends are temperature sensitive. They are stripped to 10 mm maximum. In order for the wire ends to have contact, they are twisted together, since open wire ends would not give a recording. The compatible digital temperature recording device MD 3040 (Beckmann+Egle Industrieelektronik GmbH, Kernen, Germany) was used with the temperature sensor GFT 300.

All recordings were performed in the measuring range A (measuring range −65.0 to +199.9°C, accuracy 0.2%±0.5°C, solution 0.1°C). The digital measuring device MD 3040 was connected via a serial interface (ASCII-code), aided by an interface cable MD 3042 (Beckman+Eagle Industrieelektronik GmbH, Kernen, Germany), to an IBM compatible Notebook computer. This allowed the reading of all recorded data in ASCII-code. With computer software for graphic representation of temperature values that were recorded with the digital temperature measuring appliance MD 3040, the temperature could be simultaneously traced in the form of a graphic on the PC monitor. The program could handle up to 500 measuring values, and store them in ASCII format on the hard disk within a certain recording time (interval time = selected measuring time/500 [in seconds]). The interval time = 1 was set as the time threshold, which seemed sensible for later evaluation. One measurement value was recorded each second. All measurements were performed in the Department for Operative Dentistry of the Johannes Gutenberg-University Mainz in a climate-controlled facility.

The manufacturer of the MD 3040 temperature measuring devices had both devices adjusted and calibrated. The recorded data was stored on the local hard drive after each recording, and coded according to study participant, location and date.

The objective of the examination was to record the temperature in the approximal space of teeth in vivo under various temperature conditions. A set of teeth of a healthy adult who has all of his/her teeth has 30 approximal contacts. Since "axial symmetry" exists in the upper and lower jaw, the number could be reduced to seven inter-dental spaces, and the median contact point of the central front teeth for each jaw. The measurements were conducted alternating left or right. The third molars were removed from the recordings, since shape and location deviation would not allow correct measurement. As a result, there are a total of 14 approximal spaces, seven in the upper jaw and seven in the lower, that had to be recorded. The interproximal contact between the central incisors was coded 1-1, the space between the central and lateral incisor 1-2, between the lateral incisor and the caninine 2-3, between the caninine and the first premolar 3-4. The code for the interproximal spot between the premolars was 4-5; the region between the second premolar and the first molar was 5-6; and the interproximal contact between the first and second molar was 6-7.

The temperature sensors GTF 300 were attached in the approximal space with dental floss (Dental Floss, Johnson & Johnson, USA) in such a way that sliding or moving of the sensor was not possible.

The sequence of the examination was explained to the study participants, and they were also warned that, when testing to determine the upper maximum temperature took place, they must only drink when it was safe to do, so as to prevent scalding.

No fixed dwell time was used because of the individual maximum temperature reference. The dwell time was arranged according to the participants well-being.

The data of the study participant was recorded, and a short, clinical examination of the teeth took place. All data were recorded in a log. At the beginning of each session, the glasses were examined for capacity and temperature. If the temperature corresponded with the determined maximum temperature of the respective participant, measuring was started, and the recording on the computers began.

The participant was to first start with the hot tea and take a sip, hold it in the mouth a short time and then swallow it. This was to be repeated at least four times. The temperature was recorded and controlled separately on the computer. If unusual data showed up, the correct position of the probe in the mouth was checked, if necessary corrected, and the recording was restarted. Attention was also paid to the occurrence of short temperature peaks, which were then confirmed with another sip.

After the hot tea, the participants initially were asked to adjust the temperature in their mouth with water at room temperature, to prevent a radical transition resulting in possible cracks in the enamel, or even pain. This was followed by a glass of ice water at a temperature of 0°C. Here also, the participant was asked to take a sip, hold it in the mouth for a short time and then swallow it. This had to be repeated by the participant at least four times.

Upon conclusion of the first alternating temperature stress, the participants were again allowed to drink water at a moderate temperature. Then the entire process (hot-medium-cold) was repeated with a slight change. The liquids now not only had to be held in the mouth, but also conducted directly to the approximal points, where the actual recordings for the upper and lower jaw took place. The liquid should only remain at the location as long as it was comfortable for the participant. When this second alternating temperature stress was completed, a short pause took place, until a slight upward trend could be determined, after which testing was ended. This process was repeated for all interproximal points.

A separate log was kept for all study participants, in which all the master data and the sequence of the recording data was entered. This guaranteed that each participant was initially measured at the same point.

A descriptive statistical analysis was carried out. The time spent with each participant was about 3 h. The participant had to consume on the average 0.75–1 l of tea, and about 1 l of water with crushed ice. At least one test had to be repeated on each participant for various reasons (measuring probe moved or error message from computer because of recording loss).

Results

Altogether, 55,826 temperature values were recorded for the 15 study participants, in 210 tests. Three values were removed from each test for evaluation. The first temperature value was used as the starting temperature, in addition to the highest temperature value as maximum temperature, and the lowest temperature as minimum temperature. A total of 630 temperature values were evaluated, always consisting of 210 starting temperatures, plus maximum and minimum values according to the individual and approximal space. Mean values, standard deviations, and the variation coefficient were calculated from the measuring values. The results could now be viewed from various initial findings.

A maximum incorporated temperature was determined for each of the 15 study participants. The highest temperature was recorded in participants A and E with 76°C. The lowest incorporated temperature was recorded in participant C with 65°C. The mean value was 71.7°C. The temperature span was 11°C between 65 and 76°C.

The mean value of all initial temperatures (n=210) was 35.2±1.3°C. The mean value of all minimum temperatures in the upper jaw (n=105) was 23.9±4.5°C, in the lower jaw (n=105) 24.5±4.7°C, and the mean value of the total minimum temperatures (n=210) was 24.2±4.7°C. The mean value of all maximum temperatures in the upper jaw (n=105) was 42.7±3.3°C, in the lower jaw (n=105) 44.9±3.7°C, and the mean value of the total minimum temperatures (n=210) was 43.8±3.7°C. Table 2 shows all maximum and minimum values with the respective mean values and standard deviations that were recorded on the respective participants.

The mean values of the initial temperatures in the upper jaw were lower than the corresponding temperatures in the lower jaw. The highest mean values were recorded with 35.8 and 36.0°C at the front of the lower jaw (measuring point 1-1 lower jaw), and between the first and second lower jaw molars. The lowest temperature by far was found in the upper jaw at testing spot between the central and lateral incisor with 33.9°C. Table 3 shows the total results. All mean maximum and

Table 2 Comparison of results: summary of all initial mean, maximum and minimum temperatures with standard deviation according to the respective participants

	Mean initial temp. [°C] in the upper jaw (±SD)	Mean initial temp. [°C] in the lower jaw (±SD)	Mean initial temp. [°C] total (±SD)	Mean maximum temp. [°C] in the upper jaw (±SD)	Mean maximum temp. [°C] in the lower jaw (±SD)	Mean maximum temp. [°C] total (±SD)	Mean minimum temp. [°C] in the upper jaw (±SD)	Mean minimum temp. [°C] in the lower jaw (±SD)	Mean minimum temp. [°C] total (±SD)
Volunteer A	36.1 (1.1)	36.2 (0.5)	36.2 (0.8)	42.5 (1.9)	44.8 (4.3)	43.7 (3.4)	22.3 (2.9)	24.0 (3.8)	23.2 (3.4)
Volunteer B	35.2 (1.3)	36.3 (0.8)	35.7 (1.2)	41.3 (1.8)	43.5 (2.1)	42.4 (2.2)	26.2 (3.0)	25.5 (3.3)	25.8 (3.0)
Volunteer C	33.3 (0.9)	34.1 (0.9)	33.7 (1.0)	40.3 (1.9)	41.5 (3.3)	40.9 (2.6)	28.1 (3.8)	27.1 (4.0)	27.6 (3.8)
Volunteer D	34.7 (0.8)	35.8 (0.8)	35.2 (1.0)	45.8 (4.4)	46.9 (3.6)	46.4 (3.9)	19.5 (3.6)	18.7 (4.2)	19.1 (3.8)
Volunteer E	34.0 (1.2)	36.0 (0.7)	35.0 (1.5)	40.4 (3.3)	42.4 (4.1)	41.4 (3.7)	24.0 (7.3)	26.4 (5.1)	25.2 (6.2)
Volunteer F	33.4 (2.7)	35.3 (0.5)	34.3 (2.1)	43.6 (2.3)	44.9 (3.2)	44.2 (2.8)	20.1 (4.6)	22.9 (3.4)	21.5 (4.2)
Volunteer G	34.9 (1.7)	35.7 (1.0)	35.3 (1.4)	44.6 (4.5)	46.0 (2.8)	45.3 (3.7)	24.1 (2.5)	23.5 (4.9)	23.8 (3.8)
Volunteer H	35.2 (0.6)	35.2 (0.6)	35.2 (0.6)	44.6 (3.3)	43.9 (4.0)	44.2 (3.5)	21.0 (3.9)	25.1 (5.1)	23.0 (4.9)
Volunteer I	34.9 (0.6)	35.6 (0.9)	35.2 (0.8)	43.8 (3.7)	45.6 (3.4)	44.7 (3.5)	23.8 (3.2)	24.9 (5.4)	24.4 (4.3)
Volunteer J	34.6 (1.2)	35.2 (1.0)	35.0 (1.2)	42.3 (1.7)	47.7 (2.4)	45.0 (3.4)	24.7 (2.4)	23.9 (2.2)	24.3 (2.3)
Volunteer K	34.4 (1.3)	35.2 (0.7)	34.8 (1.1)	41.1 (3.1)	44.5 (4.3)	42.8 (4.0)	26.5 (3.7)	27.3 (3.9)	26.9 (3.6)
Volunteer L	35.2 (0.4)	36.0 (0.6)	35.6 (0.7)	41.4 (3.4)	43.5 (3.8)	42.4 (3.6)	26.9 (4.4)	28.3 (3.8)	27.6 (4.0)
Volunteer M	34.9 (1.7)	36.3 (0.5)	35.6 (1.4)	41.5 (2.0)	44.8 (3.4)	43.1 (3.2)	23.5 (4.0)	24.6 (5.8)	24.1 (4.8)
Volunteer N	35.4 (0.9)	36.0 (0.5)	35.7 (0.8)	44.2 (3.4)	46.1 (3.0)	45.2 (3.2)	25.6 (4.3)	23.1 (4.7)	24.4 (4.5)
Volunteer O	34.5 (1.0)	35.1 (0.9)	34.8 (0.9)	43.1 (3.8)	48.0 (3.4)	45.5 (4.3)	22.3 (3.9)	22.1 (5.1)	22.2 (4.4)

Table 3 Comparison of results: summary of all initial mean, maximum and minimum temperatures in the upper and lower jaw depending on the testing location

Location	Mean initial temperature [C°] in the upper jaw	Mean maximum temperature [C°] in the upper jaw (±SD)	Mean minimum temperature [C°] in the upper Jaw (±SD)	Mean initial temperature [C°] in the lower jaw	Mean maximum temperature [C°] in the lower jaw (±SD)	Mean minimum temperature [C°] in the lower jaw (±SD)
1-1	34.3	44.2 (3.0)	20.5 (4.6)	35.8	45.2 (4.2)	25.3 (5.6)
1-2	33.9	44.6 (4.0)	22.8 (4.6)	35.4	43.6 (2.6)	25.5 (4.8)
2-3	34.9	42.1 (2.8)	25.3 (4.6)	35.3	44.2 (3.1)	25.8 (4.2)
3-4	35.0	41.4 (2.3)	24.1 (3.6)	35.4	44.1 (4.1)	24.2 (4.3)
4-5	34.8	42.1 (2.5)	25.1 (3.9)	35.7	46.1 (4.1)	23.9 (5.0)
5-6	34.7	41.8 (3.2)	24.8 (3.8)	35.6	45.5 (3.9)	23.8 (4.9)
6-7	35.3	42.6 (4.3)	24.8 (4.7)	36.0	45.7 (3.5)	22.8 (4.2)

minimum values with the respective standard deviations are allocated to the respective testing points.

The highest temperature was measured on participant D at testing point 4-5 in the lower jaw with 52.8°C. Participant D also showed the lowest temperature of 13.7°C in the upper jaw on testing point 1-1, as did participant F on testing point 1-2 in the upper jaw. The highest temperature was recorded in the upper jaw with 51.8°C on participant I at testing point 1-2. The lowest temperature was found on participant D in the lower jaw at testing point 1-1 with 13.9°C.

Discussion

In this current study, the mean incorporation temperature of 71.7°C was somewhat higher than described in other reports. The temperature span therefore was also slightly higher, from 65 to 76°C. A possible reason for the higher incorporated temperatures, as Gräf already formulated in his publication [15], could be the adjustment to increasingly higher temperature limits. If the publications are viewed according to the year published, a tendency in the rise of the incorporated temperature can be noticed, from Nelsen et al. in 1952 with 60°C [31] to Youngson et al. in 2000 with 72.5°C [50]. Another aspect is the absence of fillings, crowns or spaces [4, 36, 48] in the participants of this study, since due to diverse materials a faster warming of teeth would be made possible, based on better thermal conductivity. The participants were, on average, 22.2 years old and had only healthy teeth. There was no sensitivity on the neck of any tooth. With a mean value of slightly below 72°C, hot provocation is rather high, but this could be an advantage in view of the desired findings for the validation of the in vitro material tests.

There was no pilot test for cold provocation. The temperature of 0°C was in accordance with the literature [15, 26, 27, 31, 36, 42, 44, 50].

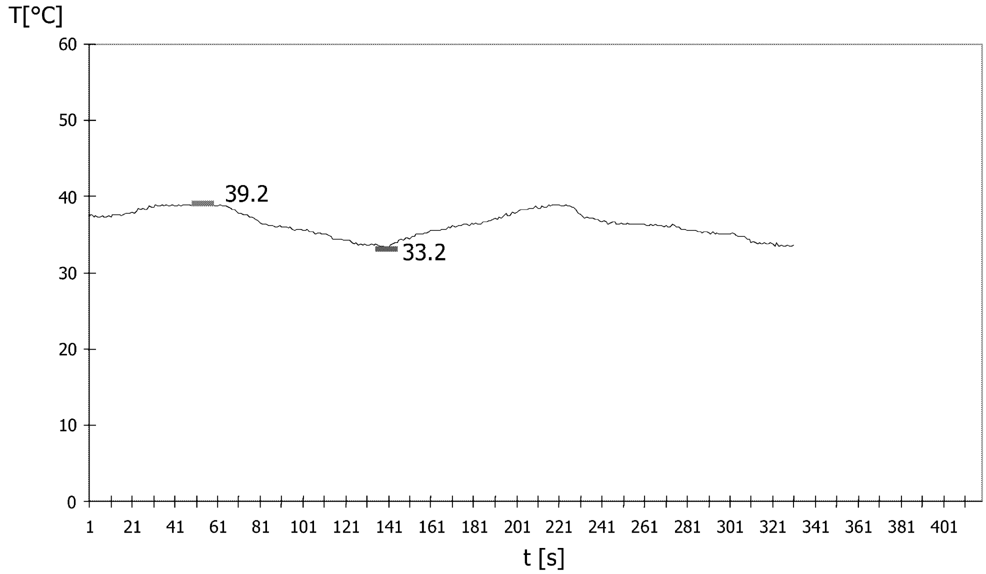
Determining the initial temperature and its evaluation represents a sideline of the research. It was not the primary objective of the study to determine the temperature of the approximal space without external influences. There are a lot of studies that dealt with oral temperature, the gingiva temperature or sulcus temperature [1, 2, 5, 26, 29, 30]. The result of this measurement, 35.2±1.3°C, is the mean value from 210 initial temperatures. The variation coefficient is very low, at 0.036. Several values in the report are below this result, e.g., 30.6°C [7], 33.1°C, 34.6°C [26]; on the other hand, others are slightly above this result, e.g., 36.2°C [5] and 36.3°C [28]. The results of the mean values of the initial temperatures specific to the location of the recording is interesting. On the one hand, the upper jaw mean value was colder by 0.9°C (upper jaw mean value 34.7°C; lower jaw mean value 35.6°C) than the lower jaw. On the other hand, the temperature increased distally in both jaws. Similar observations were also documented by Bergström and Varga [5].

A temperature span of 19.6°C was measured with a mean of 43.8±3.7°C for the maximum temperatures (n=210) and 24.2±4.6°C for the minimum temperatures (n=210). The mean values have no bearing on in vitro testing because laboratory tests are more likely to simulate extreme cases [21]. However, the mean values are interesting because they cover very well the pain-free area (initial pain at above 45°C and below 27°C) described by Hensel and Mann [18]. If 35°C (results from the present study) is taken as the initial temperature, the temperature difference upwards to 43.8°C is exactly 8.8°C, and the temperature downwards to the lower mean 24.2°C, with 10.8°C being slightly more. It is interesting that the maximum temperature mean was measured with similar temperature values by other authors [15, 28, 35]. One of the reasons could be the sequence of the hot/cold drinks.

All measurements in this study started with hot provocation, followed by the cold drink. Barker et al. [4] observed in their publication that an isolated tooth reacts to a new temperature irritation very quickly. A tooth in the oral cavity takes much longer to react because of the available ambient temperature. In reverse, it also cannot discharge the temperature as quickly because of the current ambient temperature. The surrounding structures of teeth, cheeks, tongue, lips and also the palate represent very well-circulated structures. The heat regulation of a person is, for the greater part, due to the type of circulation [47]. Another influencing factor with an effect, even if very slight, is the breath of air that enters the oral cavity on its way to the lung, and again passes through when exhaled [6].

It cannot be explained why the upper and lower jaw on the average show a different temperature when tracing the

Fig. 3 Temperature recordings of participant E, as obtained from the testing spot 4-5 in the lower jaw



provocation. Anatomical structures or the physiology of drinking and swallowing might be a possible explanation. The swallowing process, mainly initiated by the tongue, may definitely have an influence on the temperature in the mouth. Closing of the set of teeth is part of the normal act of swallowing [16, 40, 47]. Longman and Pearson [26], among others, determined that the hotter the drink was, the less of it was swallowed. The food bolus, in the first phase of the act of swallowing, is being pressed by the tongue upward against the hard palate, and from there moves in the direction of the throat [40]. Evaluation of the extreme temperatures, according to participants and measuring locations, however, showed no essential difference in the distribution of the initial, maximum and minimum temperatures.

The highest temperature was found in participant D at the testing spot 4-5 in the lower jaw, with 52.8°C. The lowest temperature was measured in participant F at testing spot 1-2 in the upper jaw, with 13.7°C. The temperature span between these two extreme temperatures is 39.1°C. The temperatures that were generally recommended for alternating temperature stress in vitro, from 5°C for cold provocation, to 55°C for hot provocation [33] were not reached in any recording. The larger space between in vitro stress of 5°C to the lowest temperature values measured in the mouth, 13.7°C, is astonishing. The difference was 8.7°C. The difference between 52.8°C, measured in the mouth, and the one used in vitro, 55°C, was only 2.2°C. A possible answer might be an arbitrarily set margin of 5 and 55°C, if one again assumes 35°C is taken as base temperature of the mouth. The difference with 55°C is only 20°C, in contrast to the difference to 5°C. However, this is 10°C more, namely 30°C.

The results recorded in this study do not seem very extreme, but it has to be considered that the testing location is the interdental space, which is surrounded on two and/or three sides, (if the contact point is included) by the tooth, and in the ideal case is completely filled out by the inter-dental papilla. Considering that, the recorded values seem then to be rather high.

This protected area is more susceptible to temperature than was expected. A temperature characteristic such as shown in Fig. 3 would be more likely. This temperature characteristic, however, was the exception (approximately 9 of 210 temperature results).

The temperature results, as shown in Figs. 1 and 2, are more likely to be the norm. Already at the first sip, the temperature increases rapidly and drops down just as rapidly after the drink is changed from hot to cold. It might be that the thermal element is not positioned correctly in the approximal space. The correct position, however, was checked before removal. Furthermore, such a temperature result is not an isolated case. It has to be noted concerning the thermal element, that a direct, visual control with the correct positioning in the approximal space, e.g., by using a separator (Aesculap, Germany), would have been impossible and/or very expensive. Thus, it was rechecked and determined that the measuring tips of the thermal element were not visible, and the dental floss attachments, before and after, remained at the respective, planned measuring location. Therefore, the idea that the measuring tips were exposed directly in the oral cavity can be excluded. It would be more likely that the measuring tips recorded the sulcus temperature.

High temperature changes can be caused by warming the tooth; a so-called isotherm is created, i.e., areas with the same temperatures. A tooth on its occlusal surface has very few isotherms. As the tooth is warming up quite evenly on its surface, the isotherms in the interior are situated parallel to the surface. However, in the cervical area many isotherms meet in a very limited space. This means that several temperatures are present in a very small area [25, 43].

Conclusion

The question was, then, *does the temperature range (5 and 55°C) of in vitro thermocycling need to be adjusted for alternate temperature stress tests?* It does not seem to be necessary for class II cavities. Since the stress in the interproximal space is, in part, so close to the upper temperature threshold, it can be assumed with some hot foods that the temperature threshold of 55°C at the tooth surface is exceeded. Youngson et al. have already formulated this claim based on their tests on one participant [50]. An adjustment of the lower threshold from 5 to 10°C does not seem to be reasonable, but it would bring the lower limit value closer to the clinically determined lowest minimum temperature. Therefore, the in vitro temperature range used widely for in vitro-testing of dental materials seems to "overstress" the interface to a certain extend, which on the other hand, seemed to be favorable over the risk of a potential "understressed" situation.

References

1. Arnold M, Cendelin E (1984) Marginale und papilläre Sulcustemperatur. Stomatologie der DDR 34:460–464
2. Arnold M, Richter K (1979) Objektivierung klinischer Befunde an der Gingiva (Objectifying of clinical diagnostic findings at the gingiva). Stomatologie der DDR 29:141–145
3. Bachmann A, Lutz F (1976) Schmelzsprünge durch die Sensibilitätsprüfung mit CO2-Schnee und Dichlor-difluormethan- eine vergleichende In-vivo-Untersuchung (Enamel cracks caused by sensitivity tests with dry ice and Dichlorodiflouromethane: a comparative in vivo study). Schweiz Mschr Zahnmed 86:1042–1059
4. Barker R, Rafoth R, Ward RW (1972) Thermally induced stresses and rapid temperature changes in teeth. J Biomed Mater Res 6:305–325
5. Bergström J, Varga G (1971) Temperatures of the oral cavity in 50 healthy students. Swed Dent J 64:157–164
6. Boehm PF (1972) Thermal environment of teeth during open-mouth respiration. J Dent Res 51:75–78
7. Brown AS, Goldberg MP (1966) Surface temperature and temperature gradients of human teeth in situ. Arch Oral Biol 11:973–982
8. Brown WS, Jacobs HR, Thompson RE (1972) Thermal fatigue in teeth. J Dent Res 51:461–467
9. Eakle WS (1986) Effects of thermal cycling on fracture strength and microleakage in teeth restored with bonded composite resin. Dent Mater 2:114–117
10. Finger W (1974) Die Wärmeausdehnung von Composite-Füllungsmaterialien und ihre klinische Bedeutung (Thermal expansion of composite restoration materials and its clinical significance). Schweiz Mschr Zahnmed 84:630–647
11. Fouke J, Wolin A, Bowman F, McFadden R (1990) Effect of facial cooling on mucosal blood flow in the mouth in humans. Clin Sci 79:307–313
12. Franke J (1951) Über Temperaturmessung in der Zahnumgebung und ihre Bedeutung für die Kenntnis der Durchblutungsverhältnisse des gesunden und erkrankten Parodontiums (Temperature measurement and its significance for acquiring blood circulation rates of healthy and inflamed parodontium in dental environment). Dtsch Zahnärtzl Z 6:1368–1375
13. Gente M, Sondermann U, Lehmann KM (1985) Linearer thermischer Ausdehnungskoeffizient von Rinderschmelz und Rinderdentin (Linear thermal expansion coefficient of bovine enamel and dentin). Dtsch Zahnärztl Z 40:488–490
14. Gente M, Sondermann U, Lehmann KM (1986) Untersuchung zur Krümmung von Schmelz-Dentin-Streifen bei Temperaturveränderung (Study of the deflection of enamel-dentin-lines during temperature changes). Dtsch Zahnärztl Z 41:847–852
15. Gräf W (1960) Die thermische Belastung der Zähne beim Verzehr extrem heißer und kalter Speisen (Thermal exposure of teeth during the consumption of extremly hot and cold food). Dtsch Zahnärztl Z 15:30–34
16. Hamlet S, Choi J, Zormeier M, Shamsa F, Stachler R, Muz J, Jones L (1996) Normal adult swallowing of liquid and viscous material: scintigraphic data on bolus transit and oropharyngeal residues. Dysphagia 11:41–47
17. Hellwig E, Klimek J, Attin T (1995) Einführung in die Zahnerhaltung (Introducing operative dentistry). Urban und Schwarzenberg
18. Hensel H, Mann G (1956) Temperaturschmerz und Wärmeleitung im menschlichen Zahn (Thermal pain and thermal conduction in human teeth). Stoma 9:76–85
19. Herrmann M (1953) Temperaturverhältnisse an der Mundschleimhaut und den Zähnen (Thermal proportions of oral mucosa and teeth). Dtsch Zahnärztl Z 8:539–543
20. Holthuis AF, Gelskey SC, Chebib FS (1981) The relationship between gingival tissue temperatures and various indicators of gingival inflammation. J Periodontol 51:187–189
21. Jacobs HR, Thompson RE, Brown WS (1973) Heat transfer in teeth. J Dent Res 52:248–252
22. Kidd E (1976) Microleakage: a review. J Dent 4:199–206
23. Kidd E (1976) Microleakage in relation to amalgam and composite restoration: a laboratory study: Brit Dent J 16:305–310
24. Klengel S, Arnold M (1992) Abhängigkeit der Gingivatemperatur vom zirkadianen Rhythmus (Temperature-dependence of the gingiva on the circadian rhythm). Zahnärztliche Praxis 9:340–343
25. Lloyd BA, McGinley MB, Brown WS (1978) Thermal stress in teeth. J Dent Res 57:571–582
26. Longman C, Pearson G (1987) Variations in tooth surface temperature in the oral cavity during fluid intake. Biomaterials 8:411–414
27. Mesu FP (1983) The effect of temperature on the compressive and tensile strengths of cements. J Prosthet Dent 49:59–62
28. Michailesco PM, Marciano J, Grieve AR, Abadie MJM (1995) An in vivo recording of variations in oral temperature during meals: a pilot study. J Prosthet Dent 73:214–218
29. Mukherjee S (1978) The temperature of the gingival sulci. J Periodontol 49:580–584
30. Nell A, Loicht Ch, Emmer W, Sperr W (1994) Ergebnisse von Temperaturmessungen im Sulcus gingivae (Results of temperature measurements in the gingival sulcus). Zeitschrift für Stomatologie 91:9–17
31. Nelsen JN, Wolcott RB, Paffenbarger GC (1952) Fluid exchange at the margins of dental restorations. J Am Dent Assoc 44:288–295
32. Øilo G (1993) Bond strength testing—what does it mean? Inter Dent J 43:492–498
33. Øilo G, Austrheim EK (1993) In vitro quality testing of dentin adhesives. ACTA Odontol Scand 51:263–269
34. Palmer DS, Barco MT, Billy EJ (1992) Temperature extremes produced orally by hot and cold liquids. J Prosthet Dent 67:325–327
35. Peterson EA, Phillips RW, Swartz ML (1966) A comparison of the physical properties of four restorative resins. J Am Dent Assoc 73:1324–1336
36. Pfeifer M, Marx R (1989) Temperaturbelastung von Adhäsivbrücken und Ihre Auswirkung auf die Verbundfestigkeit der Klebeverbindung (Thermal exposure of adhesive bridges and its effects on the bonding strength). Schweiz Mschr Zahnmed 99:782–786
37. Plant C, Jones D, Darvell B (1974) The heat evolved and temperatures attained during setting of restorative materials. Brit Dent J 17:233–238

38. Retief DH, Woods E, Jamison HC (1982) Effect of cavosurface treatment on marginal leakage in class V composite resin restorations. J Prosthet Dent 47:496–501
39. Roydhouse RH, Paxon PR (1970) Thermal changes in dimension of restorative cavities. J Dent Res 49:567–571
40. Schmidt RF, Thews G (1990) Physiologie des Menschen (Human physiology). 24. Auflage, Springer, Berlin Heidelberg New York
41. Seltzer S (1955) The penetration of microorganisms between the tooth and direct resin fillings. J Am Dent Assoc 51:560–566
42. Simmons EW, Barghi N, Muscott JR (1976) Thermocycling of pit and fissure sealants. J Dent Res 55:606–610
43. Spierings T, Peters M, Bosman F, Plasschaert A (1986) The influence of cavity geometry on heat transmission in restored teeth. J Dent 14:47–51
44. Spierings T, Peters M, Bosman F, Plasschaert A (1987) Verification of Theoretical Modeling of Heat Transmission in Teeth by in vivo Experiments. J Dent Res 66:1336–1339
45. Stettmaier K, Kinder J, Vahl J, Reinhardt KJ (1978) Untersuchungen des thermischen Verhaltens von Schmelz, Dentin und ausgewählten Dentalwerkstoffen (Evaluation of the thermal reaction of enamel, dentin and selected dental materials). Dtsch Zahnärztl Z 33:474–476
46. Tanaka T, Kamada K, Matsumura H, Atsuta M (1995) A comparison of water temperatures for thermocycling of metal-bonded resin specimens. J Prosthet Dent 74:345–349
47. Thews G, Vaupel P (1981) Wärmehaushalt. Grundriß der vegetativen Physiologie (Heat balance. Compendium of vegetative physiology). Springer, Berlin Heidelberg New York, pp 237–253
48. Tibbetts V, Schnell M, Swartz M, Phillips RW (1976) Thermal diffusion through amalgam and cement base: comparison of in vitro and in vivo measurements. J Dent Res 55:441–451
49. Volchansy A, Cleaton-Jones P (1994) Variation in oral temperature. J Oral Rehabil 21:605–611
50. Youngson C, Barclay C (2000) A pilot study of intraoral temperature changes. Clin Oral Invest 4:183–189