

Implantation of an RFID-tag into human molars to reduce hard forensic identification labor. Part 2: Physical properties

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Abstract

Modifying and implanting existing RFID-tags into extracted human molars was described previously [P. Thevissen, G. Poelman, B. Puers, M. De Cooman, G. Willems, Implantation of RFID-tag into human molars to reduce hard forensic identification labor. Part 1. Working principle, *Forensic Sci. Int.* 156 (2006)]. Maximal vertical occlusal load during which the implanted RFID-tags remain active was evaluated *in vitro*. The temperature dependency of the implanted RFID-tags was studied on the extracted teeth to find out the maximal obtainable temperature before failure and a test with embedded thermistors to verify temperature distributions. The maximal working temperature of the implanted RFID-tags was revealed and gave indications for the set-up of measuring intra oral and intra tooth temperature during the cremation of a human body. Fatigue was induced on the implanted teeth by thermocycling. The results of this investigation showed the need of putting an extra insulating layer around the modified tags before implantation. The different *in vitro* tests indicated that the implanted RFID-tags can support certain oral and forensic circumstances.

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1. Introduction

Part one of this investigation reported on the implantation of radio frequency identification tags (RFID-tags) in human upper and lower molars for identification purposes. It was also described how the commercially available RFID-tags were modified in order to be suitable for implantation. The procedure was explained in detail [1].

The implanted RFID-tags should hold at least a human life time. The earliest implantation is possible around the age of 6 and the read-out could be necessary years after death. Performing fatigue tests, such as thermocycling, give an idea of the ageing behavior of the implanted devices. In addition the forces produced during chewing, grinding and clenching are the strongest physiological powers working on teeth. Finding the maximal vertical occlusal load at which RFID-tags implanted in human teeth are still functioning, indicates whether they can resist these forces. The lethal victims of burns and fire disasters

are often strongly damaged by gases, fumes, heat and flames. Teeth and bones are the longest remaining body parts in fire. The forensic identification of these bodies is very difficult, and in severe cases the task of the forensic anthropologist and the forensic odontologist [2,3]. Their work could be simplified if implanted dental tags would work during, and after exposure to high temperatures. The registration of the behavior of the implanted RFID-tags during temperature changes and the search for their heat limits is key information in defining the real forensic application of implanted RFID-tags in human molars.

The influence of vertical occlusal load, temperature and temperature cycling on RFID-tags implanted in teeth has not been studied before. Therefore exploration tests were performed to get an idea of the limits of the implanted tags and to adjust or change the measuring instruments and investigation set-ups.

The aim of the second part of this study was to evaluate the applicability of implanted RFID-tags by studying some of the tag's physical properties, like resistance to occlusal loading, temperature changes, thermocycling, and to detect the maximal vertical occlusal load and the maximal temperature the samples can resist.

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2. Materials and methods

During evaluation, the following tag specifications were controlled with the Pet-Scan II interrogator (Easytrac-Id, Antwerpen, Belgium): existence of the acoustic signal of the interrogators' beeper, appearance of tag information on the LCD of the interrogator and correctness of the tag information appearing on the LCD [1].

2.1. Vertical occlusal load

The roots of 10 prepared teeth were imbedded in Technovit 4004 methyl methacrylate (Heraeus Kulzer, Hanau, Germany) cubes of 2 cm edge. Care was taken that the occlusal plane of each tooth was mounted parallel to the ground plane of the testing machine. The Instron 4467 universal material testing machine (Instron Corporation, Norwood, USA) with load cells of 500, 1000 and 5000 N was selected to perform this test. A 4.82 mm diameter steel sphere fixed on a specially designed plunger was placed in the Instron crosshead. This steel sphere was recuperated out of an existing bearing. At the start of each test step the sphere made unloaded contact with the centre of the occlusal plane of the tooth under examination. An exploration test was performed on one arbitrarily chosen tooth with a load cell of 500 N in steps of 10 N starting at 10 N load. The nine remaining teeth were tested with the 1000 N load cell in steps of 100 N starting at 500 N load and with the 5000 N load cell in steps of 250 N starting at 1000 N load. From the moment the desired loads were reached the plunger was lifted up to make tag read-out possible without interference from the surrounding metallic parts.

2.2. Temperature tests

Ten prepared teeth, one 8 mm tag as delivered by the manufacturer and one modified 8 mm tag were investigated.

An "exploration test" was performed on one arbitrarily selected prepared tooth, an 8 mm tag as delivered by the manufacturer and a modified 8 mm tag. The Inglis dry heat oven (Inglis Limited, Ontario, Canada) was chosen for this test because its door exists of a temperature resistant glass plate surrounded by a metal frame. Through this glass wall the RFID-

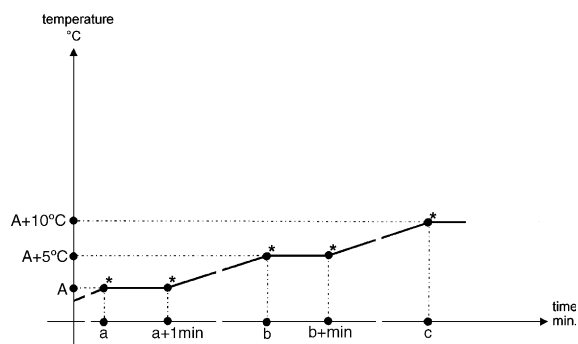


Fig. 2. Temperature/time settings during "exploration test". At the points marked with * the tag specifications were measured. During each heating up stage the time curve is interrupted because each stage lasted different.

tags can be read-out, without interference of the metallic particles, while the oven is heating. The oven has a temperature range between room temperature and 300 °C. To avoid read-out interference of the metal oven grills the samples were placed on Pyrex plates and fixed in an ideal read-out position with Technoterm no. 0554.0004 silicone paste (Fisher Elektronik, Ludenschild, Germany). This paste reduces the thermal resistance between the connecting elements up to 50% (Fig. 1). Time measurements were done with a digital chronometer. The oven was heated starting from room temperature (21 °C) till 25 °C, and then step-wise in steps of 5 °C. The temperature was kept at every stage during 1 min. The objects were read-out at the completion of every temperature step and after 1 min of constant temperature. Following every second read-out, the oven was directly heated for 5 °C extra (Fig. 2). After the second read-out on 300 °C, the oven was turned off and its door widely opened in order for it to cool down to room temperature of 21 °C. A final tag read-out was performed after 48 h.

In a second set-up, the "temperature test till 300 °C", the remaining nine prepared teeth and the in the exploration test evaluated 8 mm tag as delivered by the manufacturer, were placed together and fixed in the Inglis oven (Fig. 4). The modified tag used during the exploration test could not be examined, due to mechanical damage after it was taken out of the sticky Technoterm silicone paste. Again the oven was heated starting from room temperature (21 °C) till 25 °C, and then step-wise in steps of 25 °C. The temperature was kept at

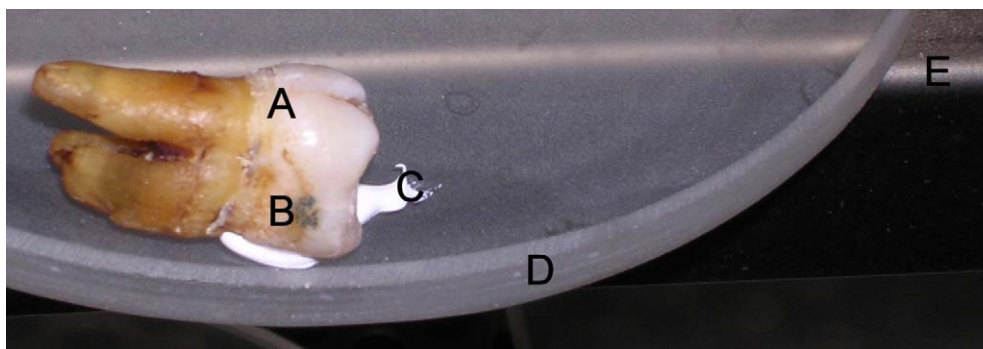


Fig. 1. Tooth position in dry heat oven. (A) Tooth; (B) mesial marking; (C) Technoterm silicone paste; (D) Pyrex plate; (E) metal oven grate. To obtain optimal tag read-out the tooth is placed with its mesial marking towards the oven door.

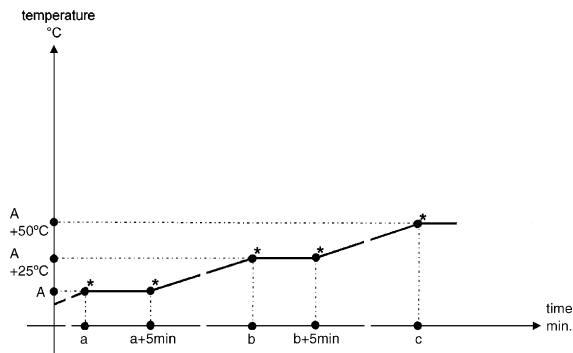


Fig. 3. Temperature/time settings during the “temperature test till 300 °C”. At the points marked with * the tag specifications were measured. During each heating up stage the time curve is interrupted because each stage lasted different.

every stage during 5 min. Read-outs occurred at the reach of every temperature step and after 5 min of constant temperature (Fig. 3). After the last read-out the oven was heated at a constant temperature of 300 °C for 180 min, and every 15 min the tag specifications were tested. Then the oven was turned out and the door was kept close for 48 h. At that moment an oven temperature equal to room temperature (22 °C) was obtained and the tags were tested again.

In the “temperature test till fail of tag read-out” the nine prepared teeth used in the previous test and the prepared tooth used in the exploration test were examined. The different teeth were separately tested and therefore fixed on a Kalorik dry heat plate, which produced temperatures around 500 °C. The samples were placed on the plate with their buccal or palatal side using the Technoterm paste. The probe of a digital thermometer (Ama-digit 14 TH 35 °C–500 °C Amarell electronic, Kreuzwertheim, Germany) was fixed in the neighborhood of the tooth under examination, with the same silicone and a heavy metal weight (Fig. 5). At a temperature of 290 °C and every 10 °C thereafter, the tag specifications were tested while it stayed on the plate. When the communication failed (temperature of delay), the tooth was taken of the plate and placed on a heat resistant shield. Then time was measured till a new tag read-out appeared (delay time). Immediately after this read-out the test sample was pressed again in the silicone paste on the plate, where the temperature was maintained at the prior temperature of delay. Then the plate was heated for 10 °C more and the sample tested as previously,



Fig. 4. Test samples placed in Anglis dry heat oven. The position of each sample was tested with the Pet-Scan II interrogator, so that there was no read-out interference with the neighboring devices.

repeatedly until tag read-out stopped (temperature of fail). Room temperature was 21 °C during the whole test.

2.3. Thermistor tests

In order to investigate and quantify the influence of the thermal mass of the implanted system a test was set-up to monitor both temperatures inside and outside the tooth. A thermistor was implanted in a tooth cavity prepared the same way as for tag implantation [1]. Supplementary holes, to lead the connecting wires through, were drilled in the remaining mesial and distal tooth wall with a round diamond drill #007 under water cooling. The temperature sensor was placed, and the cavity filled following the tag implantation procedure [1]. The remaining spaces next to the wires on the mesial and distal tooth side were filled with the Z250 composite (Filtek Z250, 3 M Espe, St. Paul, USA). The thermistor type 100K6A1D/NTC (Betatherm Corporation, Shrewsbury, USA) used in this study was composed of a central spherical body with a diameter of 1.4 mm, and two 20 mm long connecting wires. It could register a maximal temperature of 150 °C (Fig. 6). The control thermistor, the tooth with implanted thermistor and the probe of the digital thermometer were fixed with the Technoterm paste on the Kalorik dry heat plate as previously described. Each pair of wires of the thermistors were connected with a Hewlett

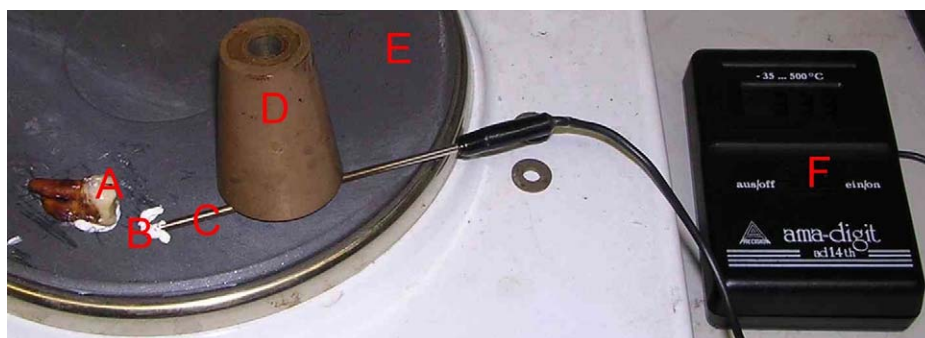


Fig. 5. Set-up “temperature test till fail of tag read-out”. (A) Tooth; (B) Technoterm silicone paste; (C) temperature reading probe; (D) weight; (E) Kalorik dry heat plate; (F) Ama-digit 14 TH thermometer.

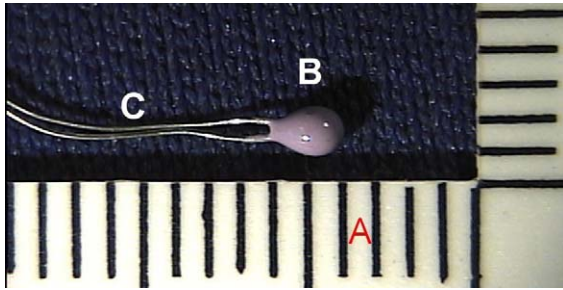


Fig. 6. Thermistor, A = 1 mm; (B) temperature sensor; (C) pliable connecting wires.

Packard 34401 A multimeter (Hewlett-Packard, Palo Alto, United States). Room temperature was 23 °C. Time was measured with a digital chronometer. This thermistor test was performed in two stages, a warming and a cooling test. During the warming test the plate was started and warmed till 140 °C. Every 10 s the resistance values of the control thermistor and the implanted thermistor were registered. During the cooling test the plate was warmed at 125 °C during 1200 s, and then turned off. From then on the resistance values of each thermistor were registered for every drop of 5 °C on the thermometer probe. The conversion of the measured resistance in Ohms to temperature in degrees Celcius was done with the 100K6A1D 100.00 Ω at 25 °C list.

2.4. Temperature cycle test

The US department of defense microcircuit test method under specification 1010.7 (MIL-STD 885E) was used [4]. During this test the devices were placed in a cold dwell at –55 °C during 15 min, heated and placed in a hot dwell at +125 °C for 15 min. One cycle includes the duration at both extreme temperatures and the two transition times. The transition time from hot to cold or cold to hot did not exceed 1 min. A Vötsch industrietechnik type VT 7012 S2 air stream oven with CTC control (Vötsch Industrietechnik, Balingen-Frommern, Germany), 10 prepared teeth and 10 12-mm tags without bioglass delivered by EasyTrack-ID (EasyTrac-ID, Antwerpen, Belgium) were used. The devices were placed in the oven in a position that there was no obstruction to the flow of air across and around the different objects. The first tag read-outs were performed at 100 cycles, afterwards every 50 following cycles.

3. Results

When the tag read-out stopped, during all the tests, the three controlled tag specifications fell out at the same time.

3.1. Vertical occlusal load

During the exploration test the read-out of the sample was positive during the 50 tested stages.

After placement of the 1000 N load cell three teeth broke due to the manual regulation of the initial sphere–tooth contact. The six remaining teeth gave a positive read-out during each of

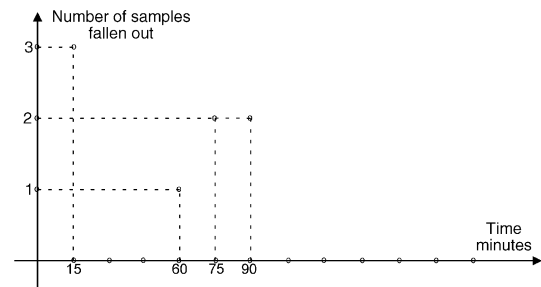


Fig. 7. Sample fall out while constant heating at 300 °C during “temperature test till 300 °C”. One of the nine implanted RFID-tags had no fall out after 180 min.

the six stages. At a pressure of 1000 N one tooth broke while the tag kept its activity. This sample couldn’t be tested further on.

The read-out of the last five implanted teeth stopped respectively at 2750, 2250, 2500, 2750, and 3150 N. The tooth of the fourth sample cracked at 2500 N, the tooth of the last sample broke at 3150 N.

3.2. Temperature tests

During the “exploration test” the three samples were tested in 112 different stages, and after opening the oven door when they reached chamber temperature. At every stage the read-outs were positive for each sample.

Every read-out was also positive for the 10 samples during “the temperature test till 300 °C”, in the 24 different heating stages and after opening the oven door.

During the constant heating at 300 °C, a fall out of the tag specifications occurred, spread over the 12 measured stages (Fig. 7). Only one implanted tag and the 8 mm tag as delivered by the manufacturer kept their activity after 180 min. Once a sample fell out, there was no more read-out in a following stage.

The detailed results of “the temperature test till fail of tag read-out” are shown in Table 1. Sample 1 gave no read-out at the start of this test, and the tooth of sample 8 broke down at a temperature of 450 °C. The mean temperature of fail is 437.5 °C (for the eight samples tested in the same conditions). The mean start of delay temperature is 392.8 °C. The mean amount of delay stages is 6.2. The mean difference between temperature of fail and temperature of first delay is 62.8 °C.

3.3. Thermistor tests

At the start of the warming test, a difference in temperature between the control thermistor and the implanted one was build up till 35 °C after 160 s heating. The temperature difference stayed constant till 450 s of warming. From that moment the difference in temperature increased and climbed to a maximum of 58 °C after 600 s (Fig. 8).

Longer heating, before the start of the cooling test (1200 s) decreased the temperature difference between the thermistors.

During the cooling test the implanted registrations stayed behind the control ones till a plate temperature of 32 °C, then the thermistors cooled down the same way as the plate (Fig. 9).

Table 1
Results temperature test till fail of tag read-out

| | Tag read-out number | Temperature of delay (°C) | Delay time (s) | Temperature of fail (°C) |
|-----|-----------------------------|---------------------------|----------------|--------------------------|
| 1 | 96700000326925 | | | |
| 2 | 96700000329696 | | | 310 |
| 3 | 96700000328988 | 370 | 4 | 450 |
| | | 380 | 18 | |
| | | 390 | 34 | |
| | | 400 | 50 | |
| | | 410 | 62 | |
| | | 420 | 70 | |
| | | 430 | 80 | |
| | | 440 | 78 | |
| 4 | 96700000335496 | 330 | 4 | 420 |
| | | 340 | 8 | |
| | | 350 | 22 | |
| | | 360 | 36 | |
| | | 370 | 45 | |
| | | 380 | 57 | |
| | | 390 | 68 | |
| | | 400 | 72 | |
| | | 410 | 76 | |
| 5 | 96700000327888 ^a | 390 | 10 | 410 |
| | | 400 | 14 | |
| 6 | 96700000331692 | 450 | 18 | 480 |
| | | 460 | 30 | |
| | | 470 | 92 | |
| 7 | 96700000329624 | 420 | 5 | 470 |
| | | 430 | 21 | |
| | | 440 | 37 | |
| | | 450 | 49 | |
| | | 460 | 60 | |
| 8 | 96700000335001 | 370 | 5 | 450 |
| | | 380 | 20 | |
| | | 390 | 22 | |
| | | 400 | 40 | |
| | | 410 | 49 | |
| | | 420 | 58 | |
| | | 430 | 62 | |
| 440 | 64 | | | |
| 9 | 96700000332079 | 380 | 4 | 450 |
| | | 390 | 14 | |
| | | 400 | 18 | |
| | | 410 | 38 | |
| | | 420 | 42 | |
| | | 430 | 48 | |
| | | 440 | 62 | |
| 10 | 96700000335592 | 430 | 24 | 470 |
| | | 440 | 26 | |
| | | 450 | 30 | |
| | | 460 | 48 | |

^a Implanted tag used in the exploration test.

3.4. Temperature cycle test

Fifty percent of the implanted tags fell out after the first 100 cycles. Therefore the next read-outs were executed after every 50 following cycles. At the initial control of the tag specifications with the Pet-Scan II interrogator, it was detected

that only 9 of the 10 received 12 mm tags without Bioglass reacted positive. The results are listed in Table 2. Once a sample fell out there was no new read-out possible after time delay. The read-out of the remaining implanted tag and the two “naked” 12 mm tags was only obtained after moving the interrogator several times over the devices.

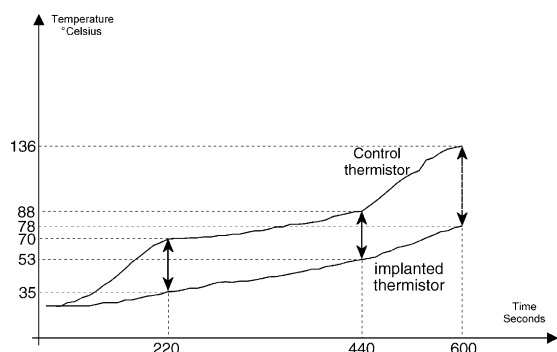


Fig. 8. Thermistor test. Warming. An almost constant temperature difference of 35 °C is seen from 220 s till 440 s heating.

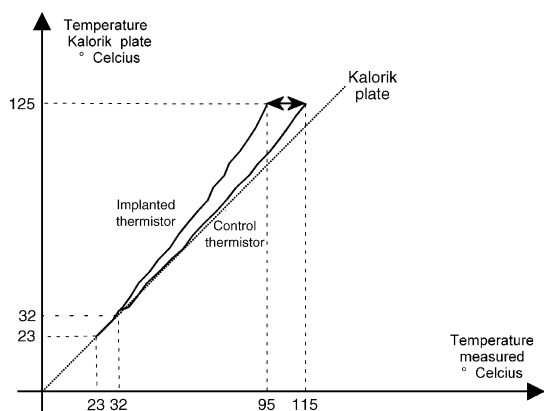


Fig. 9. Thermistor test. Cooling. The arrow indicates the temperature difference between both thermistors at the start of the test.

Table 2
Results of temperature cycle test

| Number of cycles | Number of implanted tags fallen out on total of 10 | Number of “naked” 12 mm tags fallen out on total of 9 |
|------------------|--|---|
| 0 | 0/10 | 0/9 |
| 100 | 5/10 | 0/9 |
| 200 | 6/10 | 0/9 |
| 350 | 7/10 | 2/9 |
| 400 | 8/10 | 2/9 |
| 550 | 8/10 | 3/9 |
| 600 | 8/10 | 4/9 |
| 1200 | 9/10 | 4/9 |
| 1450 | 9/10 | 7/9 |
| 2000 | 9/10 | 7/9 |

4. Discussion

4.1. Vertical occlusal load

All the tested samples were at least resistant against vertical occlusal forces of 2200 N. Since the maximum compression forces in the mouth are 500 N for premolars and 1032 N for molars [5] the conclusion is that RFID-tags implanted in teeth can stand the physiological powers working on those teeth.

4.2. Temperature tests

The RFID-tag manufacturer reports as temperature resistance a storage range from -40 to $+90$ °C up to 1000 h, and an operating range from 0 to 50 °C. The performed temperature tests revealed much better heat resistances.

During the “exploration test” the different tested devices behaved in the same way. There is no influence on the results when the device is either modified, coated by the bioglass or implanted. Although the modified device was least surrounded by materials and were exposed to most direct heat, and although the implanted tag was tightly surrounded by the composite materials and supported different thermal extensions, the expected differences did not appear. Opening the oven door at 300 °C created a thermal shock. The severe strains created in the tested devices were of no influence on the read-out results. In forensic circumstances this situation can be compared with the sudden cooling during fire-fighting.

“The temperature test till 300 °C” gave the certainty that the implanted tags can stand a heating till 300 °C. At this temperature immediate read-out is certain for at least 5 min. Longer duration of heating at 300 °C had a negative influence on the possibility of reading out the devices. However, the fall out of communication was not definitive. Lowering the temperature allowed after a certain cooling period to read-out the tags again. This loss of communication could be explained by the appearance of leakage currents within the tag’s connections. In a forensic point of view, this is an ideal situation since burned bodies can only be examined once they are taken out of the fire and are cooled down to normal temperatures.

The differences between the examined samples in “the temperature test till fail of tag read-out” were probably more due to tooth morphology and surrounding composite than tag specifications. A correlation between tooth volume or weight, amount of composite filling used and differences in failure temperature and temperature of start delay should be studied. It was not possible to calculate, with the measured parameters, at which temperature the tags cooled after fall out and became readable again. A repeated temperature of delay needs a longer cooling time before a new read-out is possible. This gives the feeling that the reading restarts once the tag reaches a constant temperature. During the tests there was no indication of the exact temperature on device level. A specific study with implantation of a tag and a thermistor in the same tooth cavity could give an exact answer. Tag 5 had a more step-wise way to reach the first 300 °C, but was not heated for 180 min at 300 °C. To evaluate the impact of these different parameters on the temperature of fail a new comparing test is necessary.

4.3. Thermistor tests

Heating time is a major parameter in the temperature behavior of the implanted thermistor. Longer heating at the same temperature decreases the difference in outer and inner tooth temperature. During both tests the temperature registered by the implanted thermistor lies behind the control registrations. This proves the thermal isolation of the surrounding

composite filling and tooth structures. In forensic circumstances an extra thermal isolation of the tooth surrounding body tissues has to be accounted for.

4.4. Temperature cycle test

Test method under specification 1010.7 was preferred to evaluate the sample under severe, forensic, temperature changes. In the dental world temperature cycle tests are mainly used as an in vitro aging test in research on effects of micro leakage, bonding strength, internal voids in restorations, and marginal adaptation of crowns. Although many reports are contradictorily 10,000 cycles of 35 °C (28 s), 15 °C (2 s), 35 °C (28 s), 45 °C (2 s) is a good estimate for an in vivo aging of 1 year [6,7].

The big difference in fall out between the modified tags and the implanted tags reveals a strong negative effect of the thermal extension and contraction on the read-out of the implanted tags. X-ray, leakage and electrical test may detect the failure during the temperature cycle test. The dental X-rays taken from the buccal, lingual, occlusal, apical, mesial and distal side of the inactive teeth were studied under microscope. They were compared with identical dental X-rays of the longest surviving implanted tag, and revealed no visual differences. The leakage and electrical tests have to be examined. It is a certainty that the surrounding bonding and composite materials effect stresses in the tags and lead to their quicker fall out. The ideal implantation should provide an isolating shield between tag and filling materials to overcome these stresses. A comparing test between a tag with bioglass coating, a modified tag, an implanted tag as described above, an implanted tag without bonding saturation, an implanted tag with a bioglass coating and a modified tag implanted with an isolating shield, such as wax, silicone paste or a thin foil, could reveal the ideal material match. It is remarkable that tags can stand temperatures of –55 °C. In some forensic cases, such as the under cooling of the passengers before the crash of the Helios Airways B737 on the 14th of August 2005, this can be of great value.

Earlier studies detected that temperature variations around the teeth during mastication and drinking hot and cold food lie between 0 and 68 °C [8–10]. The temperature tests and the thermal cycle test revealed that the implanted tags can stand these oral conditions.

5. Conclusion

For the first time physical properties on RFID-tags implanted in human teeth were studied. The results of certain tests gave a direct answer to the research item, others gave indications for modified research set-ups or new studies. Maximal vertical occlusal load and maximal temperature on which the modified and implanted tags kept working were detected.

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