Experimental determination of the emissivity of bone

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Abstract

Cutting and drilling operations in bone are involved in many orthopedic and otolaryngological surgeries. The temperature elevation of these procedures is potentially harmful to bone and soft tissue cells. The research on this topic aims therefore at minimizing temperature elevation and finding optimal process parameters. Experimental studies are mostly carried out on *ex vivo* setups using bovine bone material. For temperature measurements, either thermocouples or infrared cameras are used. Infrared cameras have potential advantages, but the emissivity value of the material has to be known. Literature values are scattered and vary within a wide range. An experimental study was carried out to quantify the emissivity using freshly frozen bovine and human bone, as well as human bone samples which were either fixed with Formalin or Thiel solution. Additionally, different surface finishes were used and emissivity was evaluated at different temperatures. The mean emissivity of bone was determined to be $\varepsilon = 0.96 \pm 0.01$ for temperature elevations up to 60°C. A slightly higher value of $\varepsilon = 0.97 \pm 0.01$ was found for temperatures around 80°C. No significant differences for human or bovine bone samples, preparation or fixation techniques were found.

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1. Introduction

Within the last decade, the research on bone drilling and sawing has regained a lot of attention. The research focuses on modelling and experimentation of cutting forces and temperature elevations [1] [2]. Especially the produced heat is of concern, because high temperatures can lead to bone necrosis (47°C for 1 minute [3]) or can harm nerves and other structures for example during head and neck (otolaryngological) surgeries [4]. Even though this topic has gained interest, no final conclusions for example on the most effective drilling parameters for reducing temperature elevation have been drawn and the research is ongoing.

In general, there are two ways to measure the heat elevation in bone: the contact and non-contact measurements. For the contact measurement, the temperature is measured with thermocouples, which are inserted into the bone close to the drilling channel. The disadvantages of contact measurements concern the contact of thermocouple and bone (normally using a thermal paste), the difficulties of precise placement and the limitation to point temperature measurements. The non-contact temperature measurements make use of pyrometers or infrared cameras and are able to read out a temperature field. However, just the surface temperature can be measured. Additionally, it is necessary to know the emissivity value of the measured material to get the correct temperature reading.

The emissivity $[\varepsilon]$ of a material is a property which provides a measure of how efficiently a surface emits energy relative to a black body. The maximum value is therefore $\varepsilon = 1$ and cannot be reached by any material. The emissivity is often called a constant, but it can vary with different factors (infrared wavelength, temperature, surface roughness, viewing angle and sample geometry) [5]. These factors are discussed later, but with some assumptions it is possible to reduce their influence. For example, when the assumption is made that a material's emissivity does not depend on wavelength, it is called a gray body emitter. If a constant can be defined, it is called the total emissivity of a material.

In the recent literature, when an infrared camera is used for bone temperature

measurement, the bone surface is either covered with a carbon spray to increase the emissivity constant, or an emissivity value is assumed. The disadvantage of using a carbon, graphite or chalk spray as done by many authors [6] [7] [8] [9] is that the exact emissivity is not known (ca. $\varepsilon = 0.95$) and the temperature fluctuation might be changed by this additional layer.

There have been some efforts to define the emissivity of bone. Stumme *et al.* [10] measured it to be $\varepsilon = 1.01$, but this value is physically invalid. Other studies defined the constant, without explaining the procedure, to be 0.99 [11] [12]. This is very unlikely because it is nearly the emissivity of a black body. To the knowledge of the author, there is no material with an emissivity of $\varepsilon = 0.99$. Another study [13] defined it to be $\varepsilon = 0.41$ which is a very low value because in general non-metal materials have a high emissivity of $\varepsilon > 0.9$ [5]. These quoted emissivity values highlight the need for a reliable value which can be used for future research.

2. Material and Methods

Before the beginning of the experiment, 18 samples (3 samples each; dimensions: ca. 20mm x (10mm to 30mm) x 2mm) were prepared. Table 1 shows an overview of the different samples, which were all cut from the cortical bone layer in the longitudinal direction. Bovine bone samples, from the tibiae of four year old cows, were acquired from a local slaughterhouse and freshly frozen. Human samples (femur of 105 year old female) were either freshly frozen or were fixed with Formalin or Thiel fixation for more than 6 months. The distinction of cut and no-cut means that the top surfaces of samples were either cut with a diamond band saw (Exakt, Germany) or the outer bone surface was left blank (tissues and periosteum were removed). Additionally, 3 samples were cut with a hand saw to create a rough surface. The aim of the different surface finishes is to evaluate if there is an influence on the emissivity because of the variety of experimental setups and preparation methods reported in literature.

Table 1: Different sample types, preparation and cutting techniques used for the evaluation of the emissivity value. Three samples were prepared for each group.

No.	Bone	Preparation	Cutting
1	Human	Fresh frozen	cut
2	Human	Fresh frozen	no cut
3	Human	Thiel Fixation	cut
4	Human	Formalin Fixation	cut
5	Bovine	Fresh frozen	cut
6	Bovine	Fresh frozen	no cut

59 For each individual experiment, three samples from different groups were
60 attached onto an aluminum plate. A thin layer of thermal conductive paste
61 (MX-4, Arctic, Switzerland) was applied in-between to ensure an even heat dis-
62 tribution. A stripe of black electrical insulating tape (Super 33+, 3M, USA)
63 with known emissivity (0.96 [14]) was attached on the top surface of the bone
64 samples so that half of the surface area is covered. The plate was then placed
65 onto a laboratory heating plate and all other surfaces around the samples were
66 covered with black chalk spray or the electrical tape to reduce reflections (ap-
67 parent temperature).

Figure 1: Left: Experimental setup with thermal camera and heating plate. A thermocouple was used for adjustment of heating plate temperature; Right: Example of three bone samples with attached reference tape.

68 A thermal camera (FLIR IR 655sc, FLIR Systems, USA) was placed verti-
69 cally over the samples in a focus distance of 0.3 m (see Figure 1). The plate
70 was heated up step wise to 40°C, 60°C and 80°C, because the emissivity should
71 be measured 20 Kelvin above room temperature [14]. The black insulation tape
72 was used as a reference because of the known emissivity constant. At least 5
73 minutes were waited after heating the plate to ensure temperature equilibrium
74 within the samples. This time period has been found sufficient in pilot tests. By
75 then, it was assumed that the tape and the bone surface had the same evenly
76 distributed temperatures. For temperature readouts, average values were used
77 from four defined areas (ca. 5 mm x 5 mm) on evenly heated parts (see Figure
78 2) of bone surface and tape. For each temperature elevation, the emissivity
79 of each bone sample was then found by changing the emissivity value in the
80 software (FLIR Research R&D) so that bone surface temperature equaled the
81 reference temperature.

Figure 2: Picture from the thermal camera showing the three samples from Figure 1 at 60°C. The average temperatures in two rectangular areas of the reference tape and bone was used to find the emissivity value for each sample.

3. Results

An analysis of covariance (ANCOVA) was carried out using temperature as a continuous and sample type as categorical explanatory variable. No conclusive differences between the different bones, preparation techniques or cutting methods were found. A small but significant trend towards higher emissivity with higher temperatures was found ($R^2 = 0.231, p < 0.001$). The emissivity values were then grouped for each temperature elevation as shown in Figure 3. A mean value of $\varepsilon = 0.96 \pm 0.01$ was found for temperature elevations of 40°C and 60°C. An increase to $\varepsilon = 0.97 \pm 0.01$ can be seen for a temperature raise to 80°C. A pairwise wilcoxon rank-sum test revealed $p < 0.05$ for the comparison of grouped data of 40°C and 60°C as well as 60°C and 80°C. A more significant value ($p < 0.001$) was found when comparing 40°C and 80°C.

Figure 3: Grouped emissivity values for each temperature elevation. A mean emissivity value of $\varepsilon = 0.96 \pm 0.01$ was found for 40°C and 60°C, while the value increased to $\varepsilon = 0.97 \pm 0.01$ for 80°C. Pairwise wilcoxon rank-sum test results are shown as well (* : $p < 0.05$; ** : $p < 0.01$; *** : $p < 0.001$)

94 4. Discussion

95 As mentioned before, the emissivity of a material can change with infrared
96 wavelength, temperature, surface roughness, viewing angle and sample geome-
97 try. Not all of these factors influence all kinds of materials, so that the wave-
98 length dependency is especially important for metals while other materials can
99 be defined as a gray body. For this experiment, the infrared wavelength of
100 the thermal camera was used ($7.5 - 14\mu m$). Additionally, the FLIR R&D pro-
101 gram corrected all temperature values with the input values of humidity, room
102 temperature and reflected environment radiation (apparent temperature). The
103 sample geometry (thickness) is important for very thin or non-opaque objects
104 because they can have a so called shine-through effect. With a thickness of 2
105 mm the samples have a sufficient thickness. The viewing angle is said to be not
106 an influencing factor as long as the viewing angle is not lower than $40^\circ - 45^\circ$
107 and the sample has therefore a so called diffuse, gray surface.

108 The used procedure to determine the emissivity constant follows the FLIR ref-
109 erence handbook [14], but should be understood as an approximation of the
110 real value. Difficulties with this procedure include the unknown uncertainty the
111 emissivity value of the tape, the equal distribution of temperature within the
112 samples, the assumption of equal temperature of bone surface and tape and the
113 manual process in finding the emissivity constant with the software.

114 To reduce some of these possible errors, an average temperature was used for
115 finding the emissivity in an area which was placed on an apparent equally dis-
116 tributed part of the bone and tape. Additionally, three different samples were
117 used for each experiment. As mentioned, no significant difference between hu-
118 man or bovine bone was found and the differences between fresh, fixation and
119 cutting techniques are within the measurement errors. A small dependency
120 ($R^2 = 0.231$) of temperature on the emissivity value was found. Further valida-
121 tion of the suggested emissivity using a larger temperature range is necessary
122 and should be facilitated in a more controlled environment (e.g. heating cham-
123 ber).

The found mean emissivity value of $\varepsilon = 0.96 - 0.97$ lies in-between the emissivities of plants and animals $\varepsilon \approx 0.95$ and human skin $\varepsilon = 0.98$ [15] and coincides with the general high emissivities of biological tissues. Hence no difference was observed for the other parameters, it is valid for bovine and human bone (and most likely for other species as well). Nevertheless we only investigated mature bones (105 year old human and 4 year old cow) so that we cannot rule out different values for younger bones. The found value should function as a first approximation and can be modified to account for different experimental environments. It should be noted, that a change in the emissivity constant of 0.01 results in a change of read temperature in 0.1-0.5°C depending on the bone temperature (higher temp $\rightarrow$ higher error).

5. Conclusion

Summarizing all the measurements, the authors recommend using an average emissivity value of $\varepsilon = 0.96 \pm 0.01$ for temperatures up to 60°C. A higher value of $\varepsilon = 0.97 \pm 0.01$ should be used for temperatures around 80°C. This temperature trend needs to be confirmed by experiments using a wider temperature range. A variety of parameters were tested and no significant differences between human, bovine, fixation (formalin, thiel and fresh) and cutting technique were found. Over all, it was possible to define the emissivity value for bone which can be used for future research.

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7. References

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