DETERMINATION OF TEMPERATURES REACHED BY TISSUES OF FACE DURING THERMOTHERAPY AND CRYOTHERAPY – SIMULATION BY THE FINITE ELEMENT METHOD

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Abstract. *Thermotherapy and cryotherapy are therapeutic modalities used by speech-language pathologists for the treatment of temporomandibular disorders. Thermotherapy is recommended for cases of muscular stress and pain and the cryotherapy for inflammation and traumas. The purpose of this investigation was to predict the temperatures reached by the tissues of the face during the application of these therapeutic modalities, by using a simulation performed in finite element software. Methods: tissues temperatures were obtained by solving Pennes' bioheat transfer equation. It was considered that the application of heat was made by an electric heating pad kept at 318.15 K, while the cryotherapy was simulated as it was applied ice and water over the skin surface. Boundary conditions were: constant temperature of 310.15 K at 0.01876 m (bone), constant temperature of 318.15 K for thermotherapy or 273.15 K for cryotherapy at 0 m (skin surface). Metabolic heat generation, blood perfusion and tissue's thermal properties were considered uniform in each tissue. It was made a one-dimensional analysis of temperature distribution in a model solved by Finite Element for Heat Transfer (FEHT) software. The model had 289 nodes and 512 elements, and it was created in a cartesian plane. Results: after 900 seconds of heat application, it was verified that the central regions of tissues reached temperatures of 316 K for skin, 314 K for fat layer, 312 K for muscle and 310.5 K for bone approximately. After 900 seconds of cryotherapy, central regions of skin reached 275.5 K, fat layer 283.5 K, muscle 297 K and bone 307 K approximately. Conclusion: It was possible to estimate the temperatures of face tissues during thermotherapy and cryotherapy by using FEHT software. The values found in thermotherapy simulation were similar to the values found in experimental researches of literature. The software is a good tool for the study of these processes and it is useful for the determination of the ideal temperatures for each modality of therapy and the duration of application, according to the goal to be reached.*

Keywords: heat transference, computer simulation, temporomandibular joint disorders, hot temperature, cryotherapy

1. INTRODUCTION

Thermotherapy consists of the heat application for therapeutic purposes. In Speech-Language Pathology, thermotherapy has been used for the treatment of temporomandibular disorders, in the cases of muscular stress and pain (Bianchini, 2000).

Heat can be applied in variable temperatures and duration from 900 to 1200 seconds. Heat application effects include vasodilatation, increase of blood flow and, consequently, of oxygenation, elimination of metabolic residues and decrease of pain. Heat also improves joint mobility and relaxes musculature. The heat source should be applied on the area of Masseter and Temporal muscles, three times a day. In dry heat application, a bag of hot water, or an electric heating pad is positioned directly on patient's skin and in moist heat application the source is involved in a moistened towel (Bianchini, 2000).

Thermodynamics principles suggest that the application of moist heat is more effective than the application of dry heat, as in heat conduction process, energy is transferred by diffusion, what involves interactions among molecules, and as larger the number of free molecules to transport the heat, more quickly the thermal conduction will happen. So, in a liquid environment, heat conduction will be quicker than in air or gas environment. However, dry heat application is simpler and this fact contributes to improve convenience and optimize compliance (Poindexter *et al*, 2002).

In a study, dry heat and moist heat were applied on patient's face through a commercial heating pad alternately for 1200 seconds intervals. The application sequence was randomized and all individuals received both moist and dry modalities. The heating pad temperature was not described, but, it is known that the individuals should alert the investigator if at some moment during the test the amount of applied heat was intolerable. It was verified that, in approximately 300 seconds, extraoral temperature reached maximum values (312.95 K to 313.26 K) and it kept stable. Intraoral temperature reached maximum values (309.26 K to 310.37 K) after 1800 seconds of heat application. There was no significant difference between both modalities of heat application (Poindexter *et al*, 2002).

Another research compared the clinical effects of two techniques of moist heat application, electric pad and towels moistened in hot water, on the symptoms of acute temporomandibular disorder. Thirty one percent of the individuals that were submitted to moist heat application did not need another treatment. This fact indicates that moist heat application is effective in the treatment of acute temporomandibular disorder (Nelson *et al.*, 1991).

Thermotherapy is contraindicated in cases of inflammation and traumas. In these cases cryotherapy is recommended. Cryotherapy is the therapeutic application of any substance to the body, resulting in a loss of corporal heat and, through that, lowering tissues temperature. Its application causes vasoconstriction and, consequently, decreases the inflammation and reduces cellular metabolism. It also causes analgesia due to the decrease of the speed of nociceptive stimuli propagation. Cryotherapy can be made through compresses, bags of ice, cold water or cryogenic sprays (Carreiro and Felício, 2001).

There is a clinically important direct relationship between adipose thickness and required cooling time. Subcutaneous adipose tissue insulates the body against heat loss. So, individual differences in adipose tissue thickness result in different degrees of insulation. For example, to decrease intramuscular temperature 7 K from baseline, a 1500-seconds treatment may be adequate for a patient with a skinfold of 0.02 m or less; however, a 2400-seconds application is required to produce similar results in a patients with skinfolds between 0.021 and 0.030 m, whereas a 3600-seconds application is required for patients with skinfolds of 0.030 to 0.040 m (Otte *et al.*, 2002).

Due to the shortage of studies regarding to the heat transfer in face tissues and due to the professionals' necessity in determining the ideal temperatures to be used in therapy, the purpose of this investigation was to predict the temperatures reached by the tissues of the face during the application of these therapeutic modalities (thermotherapy and cryotherapy), by using a simulation performed in finite element software.

2. METHODS

It was made a one-dimensional analysis of temperature distribution in a model that represents the tissue's layers of the face after thermotherapy (Case 1) and cryotherapy (Case 2) application.

The model was developed in Finite Element for Heat Transfer (FEHT) software, comprising of 289 nodes and 512 elements, and it was created in a cartesian plane.

The temperatures in the layers of skin, fat, muscular and bone tissues were obtained by solving the bioheat equation - Pennes equation, Eq. (1), (Incropera *et al.*, 2008). It is an equation of heat transfer with specific terms for heat generation due to metabolism and also due to blood perfusion.

$$\rho\, c_P\, \frac{\partial T}{\partial t} = \nabla\,(K \nabla T) + (\rho\omega)_b\, C_{P_b}(T_b - T) + \dot{q}_{met} \tag{1}$$

In this equation, ρ refers to tissue density, Cp refers to specific heat, t is time, T temperature, K conductivity, b is related to blood, ω refers to blood perfusion and $\dot{q}_{met}$ is the rate of metabolic heat generation.

It was considered that the application of heat was made by an electric heating pad kept at 318.15 K, while the cryotherapy was simulated as it was applied ice and water over the skin surface (constant temperature of 273.15 K). Boundary conditions were: constant temperature of 310.15 K at 0.01876 m (bone), constant temperature of 318.15 K for thermotherapy or 273.15 K for cryotherapy at 0 m (skin surface).

Deep body temperature is relatively constant; despite of wide fluctuations in environmental conditions and, in human, this is close to 310.15 K. In contrast, skin and superficial tissues are very influenced by environmental temperatures and are seldom constant (Childs *et al.*, 1999). That is why it was stipulated that the initial temperatures would be 308.15 K for skin, 309.15 K for fat tissue and 310.15 K for muscular and bone tissues.

For the simulation accomplishment, it was considered the average thickness of Masseter muscle (approximately 0.010 m) obtained in Brazilian individuals without alterations of temporomandibular joint (Pereira *et al.*, 2007) and jaw thickness, in condylar region, which is near 0.0059 m in men and 0.00585 m in women (Narlin *et al.*, 2009).

It is important to emphasize that the thickness of face tissues vary with sex, age, nutritional state, race, region of the face and muscular relaxation. The thickness of the soft tissue of the face, in other words, the sum of the thickness of skin, fat and muscle can vary from 0.0049 m in the frontal eminence up to 0.0164 m in the inferior lips in Brazilian men and from 0.0039 m to 0.0144 m respectively in Brazilian women (Tedeschi-Oliveira *et al.*, 2009).

Metabolic heat generation, blood perfusion and tissue's thermal properties were considered uniform in each tissue.

Thermophysical properties, physiologic parameters and thickness of face tissues are shown in Tab. 1. The properties were obtained from Sejrsen (1972), Wilson and Spence, (1988) and Collins *et al.* (2004) researches.

Table 1. Thermophysical properties, physiologic parameters and thickness of tissues

Tissue	Thickness (m)	Cp (J/kg.K)	K (W/mK)	ρ (kg/m^3)	ω (Kg/ m³.s)
Skin	0.00116	3150	0.342	1100	2.0
Fat	0.0029	2300	0.25	916	0.6
Muscle	0.0097	3720	0.4975	1041	0.125
Bone	0.005	1300	0.65	1850	0.0

3. RESULTS

Figure 1 shows tissues temperature evolution over time during thermotherapy in the central region of each tissue.

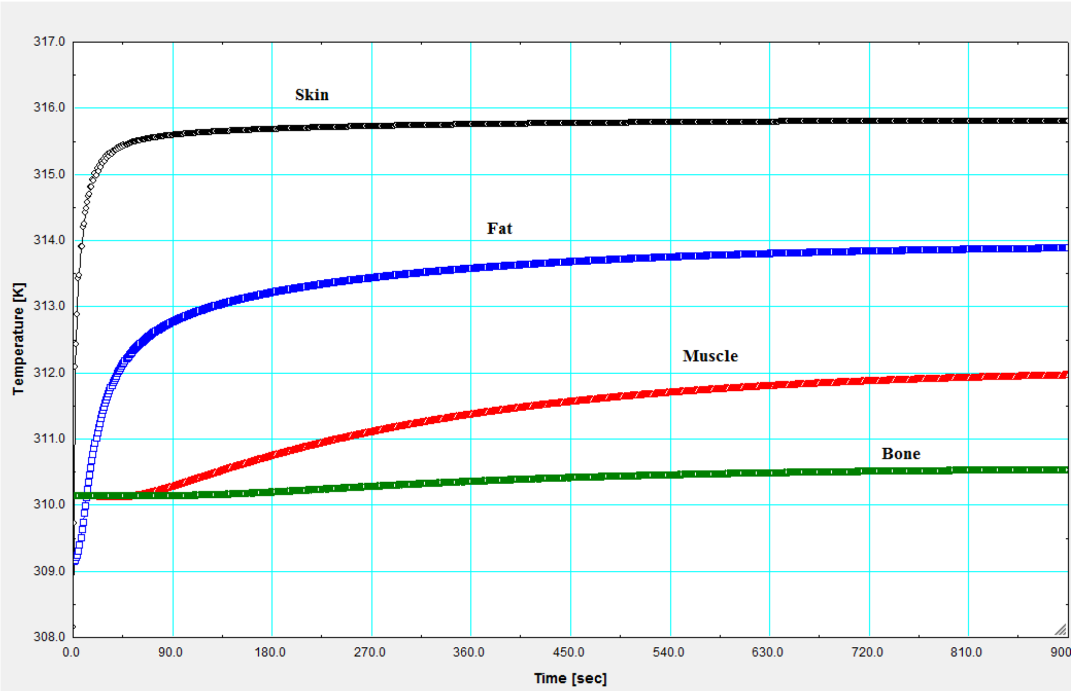

Figure 1: Distribution of temperature (K) x time (s) during thermotherapy

After 900 seconds of heat application, it was verified that the central regions of tissues reached temperatures of 316 K for skin, 314 K for fat layer, 312 K for muscle and 310.5 K for bone approximately.

Figure 2 shows tissues temperature evolution over time, in central region of each tissue, during cryotherapy.

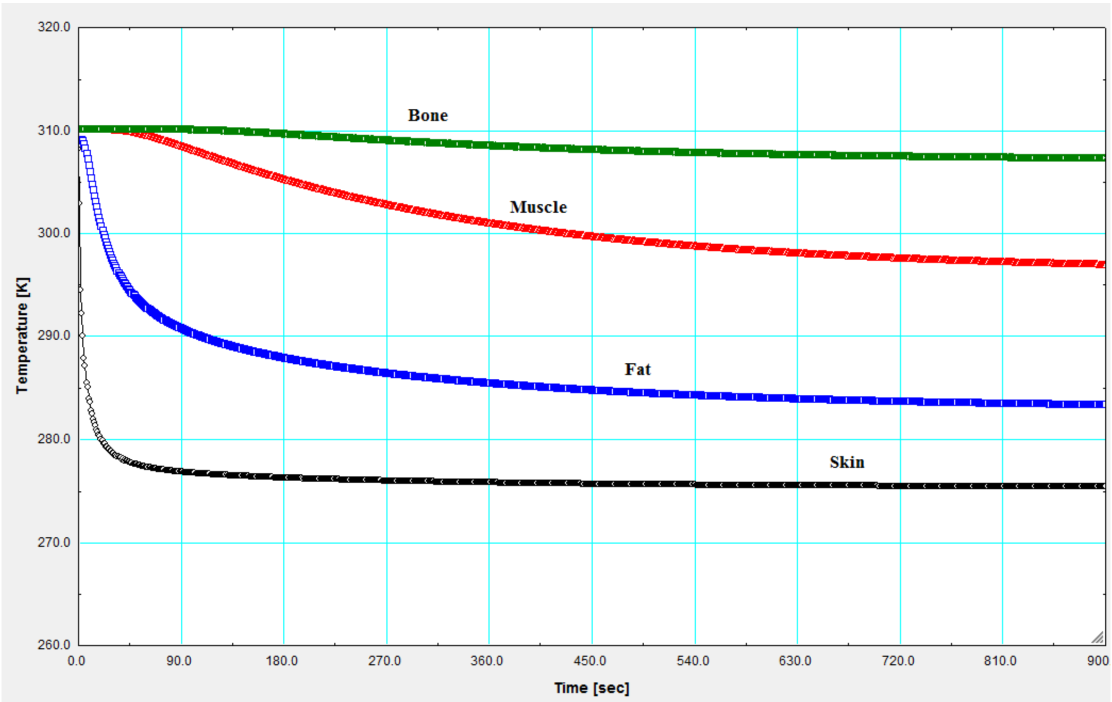

Figure 2: Distribution of temperature (K) x time (s) during Cryotherapy.

After 900 seconds of cryotherapy, central regions of skin reached 275.5 K, fat layer 283.5 K, muscle 297 K and bone 307 K, approximately.

4. DISCUSSION

To know the exactly temperatures reached by the tissues during the therapy with hot or cold stimuli application is important for the good planning of the technique to be used avoiding two kind of situations: the first regarding to the therapy that doesn't reach its final objective because the ideal temperature for that treatment was not reached or, in the second case, the therapy that causes discomfort to the patient or even damages to the tissues.

Nine hundred seconds was chosen because this time interval is commonly used clinically and because observations have shown that minimal patient discomfort within this time frame has resulted in high patient compliance (Belitsky *et al*., 1987).

An evaluation of the results presented in Fig. 1 shows that the average temperatures of all layers increased as the time progressed and such increase was more pronounced and faster for the skin and fat layers. This is attributed to the fact that such layers were closer to the heat source. The bone temperature remained practically constant. This is due to the fact that this layer was the one located farther from the heat source and also to its lower heat capacity in comparison to the other tissues (skin, fat and muscle).

The temperature reached by muscular tissue after 900 seconds of heat application, 312 K, was similar to the values found in the research accomplished by Draper *et al.* (1999). These authors verified that maximum temperatures of muscle, at the depth from 0.03 to 0.05 m, in the knee, reached 312.95 K after 900 seconds of diathermy, which is the heat application through electric current. Another study using ultrasound and diathermy verified that tissues temperature stabilized between 312.15 K and 314.15 K. The authors believe that stabilization occur because of the increase of blood flow that happens in order to prevent damages to the tissues at high temperatures (Draper *et al*., 1995).

Skin tissue reached 316 K, which was considered uncomfortable by Draper *et al.* (2004). However Lehmann and deLateur, 1989 apud Draper *et al.* (2004) suggest that for optimal heating to occur tissue temperature must reach between 313.15 K and 318.15 K. These values agree with the values for skin and fat tissues found in this simulation.

In cryotherapy, decrease of cellular metabolism and analgesia can be noticed when skin temperature is close to 283.15 K. (Sapega *et al*., 1988; Belitski *et al*., 1987; Bugaj, 1975). According to Mohr *et al.* (2009) temperature cannot reach values smaller than 271.15 K to avoid injuries. Figure 2 shows that, at approximately 30 seconds, the skin reached the desired temperature for the occurrence of the first effects of cryotherapy and it didn't cross the limit of tolerance described by Mohr *et al.* (2009) as the temperature stabilized in about 275.65 K after 180 seconds of stimulation.

It can be observed, in Fig. 2, that the higher and faster changes in temperature, during cryotherapy, also happened in outer tissues layers (fat and skin) which were closer to the cold source (ice/water pack), while bone temperature remained practically constant due to its distance from the cold source and to its lower specific heat.

Skin temperature decreased drastically at the beginning of cryotherapy application, while muscular temperature presented a slow and gradual decline. The abrupt fall of the skin temperature compared to the muscular temperature can be explained by two factors: the temperature difference between the stimuli (ice and water) and the skin which is in direct contact with the stimuli; and the vasoconstriction induced firstly in the superficial layer.

However, the temperature values reached by skin disagree with those of other experimental studies. Belitsky *et al.* (1987) observing the temperature changes on skin overlying the right triceps muscle of 10 women noticed that mean skin temperatures reached 293.25 K after 900 seconds of cold application (ice flakes enclosed in a plastic bag). Chesterton *et al.* (2002) compared the localized skin-cooling effects of two cryotherapy modalities applied in the leg of 20 volunteers: a frozen gel pack and a packet of frozen peas. After 600 seconds of cold application the packet of frozen peas produced lower temperature values on skin (283.95 K) than the frozen gel pack (287.55 K) (Chesterton *et al*., 2002). Another study verified that, the mean skin surface temperature in leg at the 1200th second of cryotherapy application with an ice pack was 283.35 K (Kanlayanaphotporn and Janwantanakul, 2005). Muscular temperature reached about 297 K in this cryotherapy simulation. This value disagrees with that obtained by Dykstra *et al.* (2009). These authors applied packs containing ice and water over the skin on the posterior aspect of the right gastrocnemius for 1200 seconds and found temperature values about 303.45 K.

The temperatures obtained in this simulation for adipose tissue were 283 K approximately, what also disagrees with the experimental values verified by Merrick *et al.* (2003) that found values of 300.36 K in adipose tissue at 0.01 m of depth and 303.74 K at 0.02 m of depth after 1800 seconds of cold application through and ice and water bag. These differences can be due, mainly, to the fact of it was simulated the application of ice and water in a constant temperature of 273.15 K and the temperature of the cryogenic bag used in experimental studies higher than 273.15 K.

In clinical practice, tissue temperature reductions achieved by the use of topically applied cryotherapy will vary considerably according to the individual patient, the body part, the protocol, and the technique used (Chesterton *et al*., 2002).

Simulations are recommended in the planning of the treatment. Nevertheless, to ensure the desired therapeutic target is reached during treatment, objective measures of tissue temperature are necessary. The results obtained in this cryotherapy simulation were not compatible with the experimental studies from literature; however, the conditions of the anterior studies were different from the simulated conditions. In next stage, experimental studies, in vivo, will be performed in the same conditions of the simulations.

The results obtained in thermotherapy simulation were compatible with the values found in literature which demonstrates that the simulation is a good tool for the study of these processes, and it could be used in practice clinic to determine the ideal temperature of the stimuli, as well as the duration of the application, according to the target to be reached.

5. CONCLUSION

It was possible to estimate objectively the temperatures of face tissues during thermotherapy and cryotherapy by using FEHT software.

In both modalities, the higher and faster changes in temperature happened in outer tissues layers (fat and skin) which were closer to the heat source, while bone layer temperature remained practically constant.

The values found in thermotherapy simulation were similar to the values found in experimental researches from literature. But, the results obtained in this cryotherapy simulation were not compatible with experimental studies from literature; however, the conditions of cryotherapy studies were different from the simulated conditions.

The software is a good tool for the study of these processes and it is useful for the determination of the ideal temperatures for each modality of therapy and the duration of application, according to the goal to be reached.

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7. RESPONSIBILITY NOTICE

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