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Simulation of cryolipolysis as a novel method for noninvasive fat layer reduction

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Background/aim: Regarding previous problems in conventional liposuction methods, the need for development of new fat removal operations was appreciated. In this study we are going to simulate one of the novel methods, cryolipolysis, aimed to tackle those drawbacks.

Materials and methods: We think that simulation of clinical procedures contributes considerably in efficacious performance of the operations. To do this we have attempted to simulate temperature distribution in a sample fat of the human body. Using Abaqus software we have presented the graphical display of temperature–time variations within the medium.

Results: Findings of our simulation indicate that tissue temperature decreases after cold exposure of about 30 min. It can be seen that the minimum temperature of tissue occurs in shallow layers of the sample and the temperature in deeper layers of the sample remains nearly unchanged. It is clear that cold exposure time of more than the specific time ($t > 30$ min) does not result in considerable changes.

Conclusion: Numerous clinical studies have proved the efficacy of cryolipolysis. This noninvasive technique has eliminated some of drawbacks of conventional methods. Findings of our simulation clearly prove the efficiency of this method, especially for superficial fat layers.

Key words: Abacus, adipocytes, cryolipolysis, fat reduction

1. Introduction

Nowadays fat removal surgeries are among the most popular cosmetic operations. With increasing demand for fat removal and body sculpting, fat removal techniques including laser liposuction have remained the most common surgical aesthetic operations in the United States and Latin America (1). Laser liposuction is a suitable method for removing fat deposits on large scales. Simultaneous interaction of laser radiation with dermal tissue triggers skin retraction. This in turn leads to skin tightening and removal of the side effect of skin laxity (2,3). However, this method is an invasive one and some unwanted side effects, including bruising, edema, and scars and long 'downtime' from daily activities, have made it necessary to develop new noninvasive methods.

Cryolipolysis is a response to these stepped-up needs. It is based on some clinical observations in infants and in adults who participate in equestrian activities in cold weather. It is documented that by exposing tissue to controlled heat extraction in proper conditions, the localized inflammation of subcutaneous fat can be triggered. Adipocytes undergo a severe apoptotic process following cold exposing. Injured adipocytes then suffer from an inflammatory clearing procedure (4,5). Subsequently, about 3 days after cold exposure, this cold-induced inflammation is terminated in perivascular infiltration of histiocytes and lymphocytes at the dermal–subdermal junction that ultimately extends into the subcutaneous fat tissue (6). This also results in lobular panniculitis (5). Changes in adipocytes increase considerably within 14 days with the appearance of more inflammatory cells in fat, the rupture of some of those cells, and the accumulation of lipids (6). Following cold exposure, between 14 and 30 days, the inflammatory response is intensified with the infiltration of many more histiocytes, neutrophils, lymphocytes, and other mononuclear phagocytosis cells, engulfing the adipose tissue cells and digesting the apoptotic adipocytes and eliminating them from the body. Consequently the average sizes of adipocytes are decreased and a wider range of adipocyte sizes is created (5,6). Within 60 days after treatment the inflammatory response is attenuated and the interlobular septae appear to be thickened significantly. The inflammatory process is decreased more and the septum forms a majority of the subcutaneous tissue 90 days following cold exposure treatment (6).

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Considering the earlier reports about temporary alterations in sensory nerve functions following the cryolipolysis process, a study was conducted by Coleman et al. to evaluate its effects on sensory function. The time duration of the occurred alterations in sensory nerves' functioning was also examined (7). Their findings indicated that cryolipolysis leads to a transient reduction in sensory function in 67% of subjects. However, these changes in sensory nerves were resolved within 1–6 weeks following heat extraction and none of the subjects suffered any permanent deficiencies (7).

Because of the increasing demand for noninvasive fat removal procedures, studies related to optimal and safe performance of these operations are of significant importance. Numerous clinical studies have examined cryolipolysis and its mechanisms (7,8). To our knowledge, however, no article has reported the simulation of cryolipolysis. Simulation of the physical processes governing cryolipolysis is our basic aim in this study. Regarding the increased demand for such cosmetic operations, studies of these type are of inherent value. According to some physicians, simulated findings and data may not be dependable sources for clinical applications; however, they provide valuable insight about the physical procedures of the therapeutic processes and also supply some good and reliable standards for operations. All of these points make simulation of physical and clinical procedures a respectable field in research areas. We think that simulation of this procedure will help in a better understanding of its behavior. Clearly it will also provide some criteria for the safe and efficacious performance of the procedure.

2. Materials and methods

In this study, we have tried to simulate the distribution of temperature within a $10 \times 10 \times 30$ mm^3 sample of human body fat, which contains epidermis, dermis, and fat layers (Figure 1). To do this, we have exploited the Abaqus software for graphical display of the parameters of interest, including temperature variations inside the medium. Abaqus is software that uses the finite element method (FEM) to solve partial differential equations (PDEs). The equation governing thermal distribution in specific media is heat transfer. The FEM is a mathematical technique that uses trial test functions for local elements to solve PDEs. To solve PDEs in this method, one needs to define the functional form of them and also it is necessary to mesh the model geometry.

The equation governing temperature distribution in specific media is heat transfer, which has been simulated in Abaqus using the FEM. Thermal conductivity, density, and specific heat of human fat tissue have been used in this simulation. The considered sample consisted of three layers of epidermis, dermis, and fat, where the initial temperatures of these layers were 307, 308, and 310 K, respectively. The dimensions and structure of the sample are presented in Figure 1, illustrating the aforementioned layers. Considering the average surface of 1.7 m^2, the human body propagates total heat of 80 W, which results in heat flux of = 0.00047 W for our simulated sample.

Generally a bioheat equation is used to examine heat distribution within biological tissues. Bioheat is a PDE that defines temperature variations and it contains a source term for external heat. However, when one is working with biological tissue, he or she must consider heat flows due to blood circulation. The Pennes equation is a modified form of the bioheat equation that considers heat extraction due to blood circulation. However, when it comes to use cryolipolysis, we have cold exposure rather than a heat source, so we must modify that source with a negative term:

$$C_p \frac{\partial T}{\partial t} - k\nabla^2 T = Q_b,\ Q_b = P\ {}_b C_b (T - T_b).$$

In this equation, represents heat dissipation through blood circulation and is the Pennes term. denotes tissue density, is specific heat capacity of tissue, and is tissue thermal conductivity. , , and are blood pumping rate, blood density, and blood specific heat capacity, respectively. As mentioned earlier, this research is a simulation work and the software we have used automatically considers the term of blood circulation. As we have considered here a negative heat source term, this additional term tends to balance the sample temperature. However, as reported in some studies, before heat extraction a vacuum must be generated by a special device. Doing so offers two great

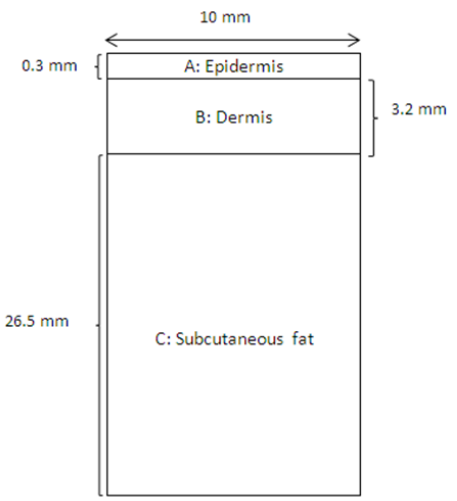

Figure 1. A tissue sample was used in the simulation.

advantages: correct tissue positioning becomes easier and the local blood flow is reduced, and this results in reduction in heat providing the effect of blood circulation. The last is mandatory for we need to reduce adipose tissue temperature down to the lipocryolysis therapeutic range (9,10).

In order to simulate the temperature distribution, we first defined the geometry of our sample in Abaqus. We did this in the 'part' module of Abaqus. The physical properties and constants such as thermal conductivity were defined in the 'property' module. Using the 'step' module and the 'transient state' of the 'heat transfer' analysis procedure, we determined the solving approach. In order to use the transient state analysis, it is necessary to import the Stefan–Boltzmann constant and absolute zero temperature into the simulation. The parameter named 'surface film condition' defines convection from the model surfaces and has been fixed in the 'interaction' module. It is also possible to use the 'concentrated film conditions' to simulate the convection from nodes or vertices. The parameter 'emissivity' indicates the radiative heat from surfaces. It generally depends on the surface temperature and surface material geometry, which has been fixed in the 'interaction' module of the software [4]. In order to define the heat flux out of the sample, we exploit the 'load' module. Determination of the boundary conditions of skin surface temperature is also done in this module. As we mentioned earlier, for solving problems by using FEM, one must mesh the geometry of the sample (tissue). In this simulation, we used the 'standard linear heat transfer' mesh type in such a way that for thinner layers of the sample we have finer mesh elements (Figure 2). This greatly increases the accuracy of the results, but slightly increases running procedures.

3. Results

We conducted the simulation of heat distribution within the tissue by Abaqus software and then we reported the results in Excel in order to show our data in a series of plots of temperature versus time. For a qualitative understanding of how temperature varies inside the tissue, we applied different temperatures on the sample surface and then examined heat distribution within layers of the tissue. The first considered step is to reduce the sample (tissue) surface temperature to –5, 0, 5, 10, 15, and 20 °C.

The diagram of temperature versus time for a surface temperature of 5 °C is presented in Figure 3. This diagram shows how temperature varies with time for the specific depths of 10 and 28 mm below the tissue surface. Results of this simulation indicate that temperature is reduced exponentially with increasing time. It can be seen that temperature reaches 23.44 °C and 29.018 °C at depths of 10 and 28 mm, respectively, following 45 min of the cooling process. Results of our simulation indicate that this procedure is not very effective at deep layers; temperature was decreased more tangibly at a depth of 10 mm and this

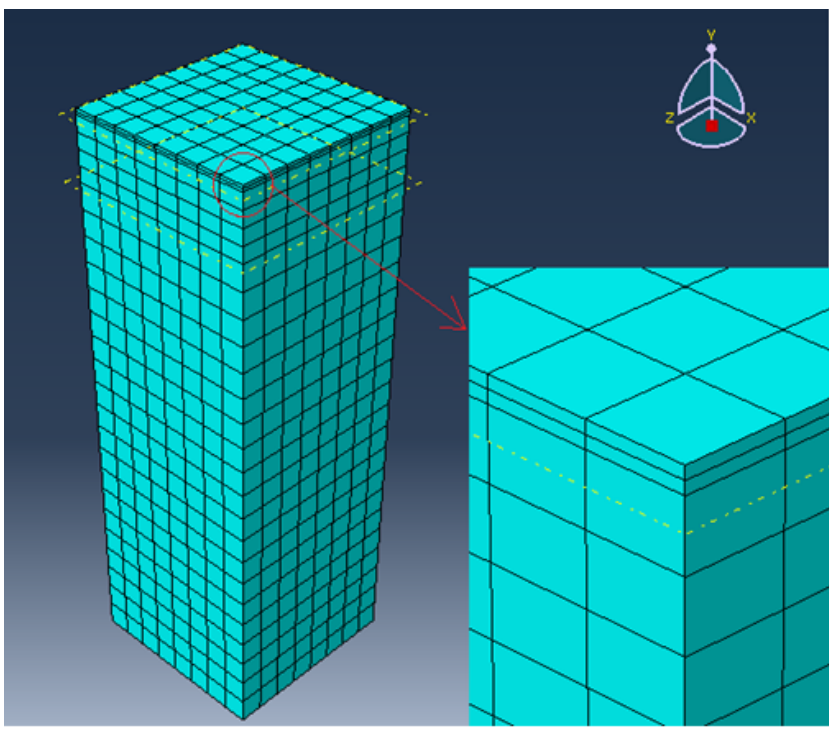

Figure 2. The meshes used in our sample.

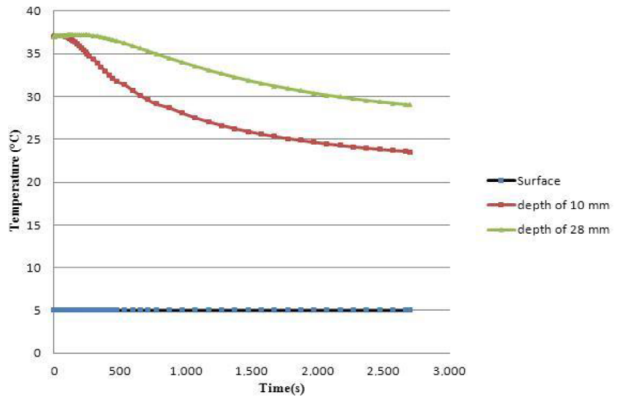

Figure 3. Temperature variations versus time, in various depths of the sample for surface temperature of 5 °C.

led to better cryogenic effects. Similar analysis was done for surface temperatures of 10, 15, and 20 °C. Our simulation outcomes for these temperatures are presented in Figures 4–6 and the Table. The results indicate that temperature variation in deeper layers of tissue is not very considerable, and at times longer than a specific time, temperature does

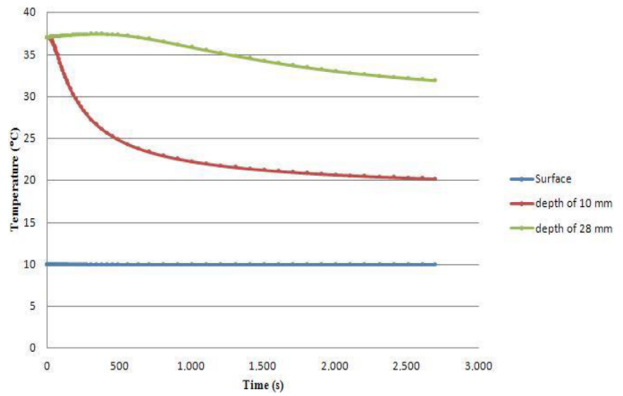

Figure 4. Time variation of temperature at various depths of the sample for surface temperature of 15 °C.

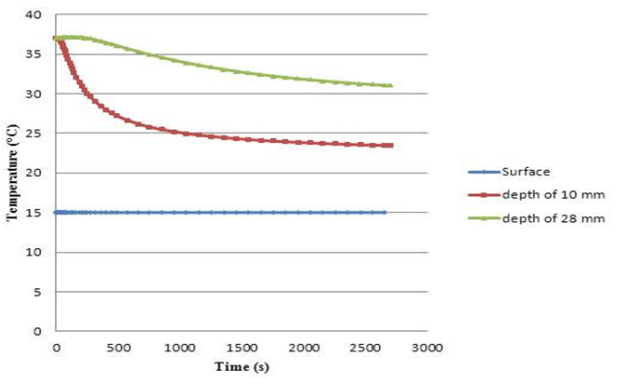

Figure 5. Time variation of temperature at various depths of the sample for surface temperature of 15 °C.

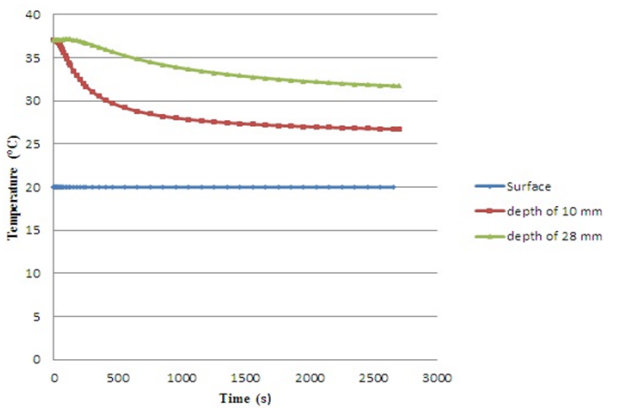

Figure 6. Time variation of temperature at various depths of the sample for surface temperature of 20 °C.

Table. Temperatures at different depths for the reported tissue surface temperature.

Temperature	Depth of 10 mm	Depth of 28 mm
5 °C	23.44 °C	29.018 °C
10 °C	20.175 °C	31.906 °C
15 °C	23.449 °C	31.039 °C
20 °C	26.722 °C	31.714 °C

not vary significantly, which suggests the value of defining a certain threshold time value. This is why surgeons typically use cold exposure of 30 min.

In order to obtain comparative criteria for the procedure, temperature variation at a depth of 10 mm for different surface temperatures is presented in Figure 7. For this purpose, we set the temperature at –5, 0, 10, and 20 °C and then applied it for 10 min on the sample. We noticed that temperature was consistently decreased

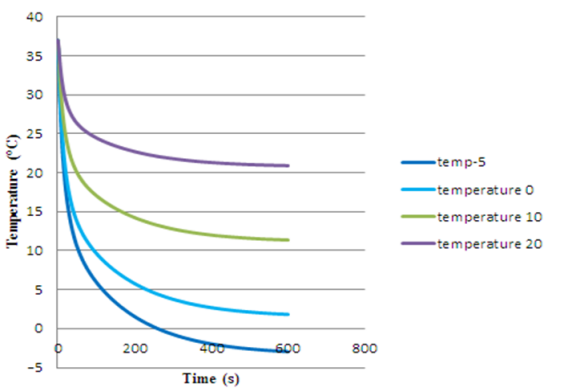

Figure 7. Comparison of temperature variation versus time for various temperatures at depth of 10 mm below the surface.

with time. At a depth of 10 mm below the surface, the minimum temperature was –2.951 °C. It was found for a surface temperature of –5 °C. Conversely, the maximum temperature of 20.294 °C was obtained for a surface temperature of 20 °C. Our data are well matched with clinical reports. Superficial temperatures correlate well with the temperatures achieved inside the adipocytes, according to some reported studies. With cooling up to 3.1 °C in the epidermis for a duration of 25 to 35 min, an intraadipocyte temperature below 10.4 °C will always be achievable (10). These temperatures are sufficient for triggering desired damages in adipocytes (9,10).

A schematic view of temperature distribution within the tissue sample following 45 min of cold exposure is presented in Figure 8. The surface temperature was set at 10 °C. It can be seen that the tissue temperature reaches values of 20.176, 28.45, and 31.394 °C at depths of 10, 20, and 28 mm, respectively. It is obvious that the tissue suffers from fewer temperature variations in deeper layers of the sample.

4. Discussion

Cryolipolysis is a novel noninvasive fat reduction treatment that effectively reduces body localized and discrete fat deposits. This method, as an outpatient one, uses controlled heat extraction and results in effective and mostly selective damage to the fat tissue. Visual, photographic, and ultrasound imaging have proved significant fat reduction in this method and no adverse side effects have been reported (6). This therapeutic process does produce some transient adverse effects such as erythema, edema, and bruising, but these all resolve within the next few days after treatment (5,6). No cases of permanent ulcerations or scars have been reported (5). There is also no need for downtime and patients can resume normal activities immediately following the procedure (6).

Pinto et al. performed a clinical study measuring the efficacy of cryolipolysis. They chose 16 women and divided them into two groups; G1 consisted of 8 women with mean basal skinfold of about 36 ± 3.5 mm, and G2 consisted of 8 women with basal mean skinfold of 36.4 ± 3 mm. Following

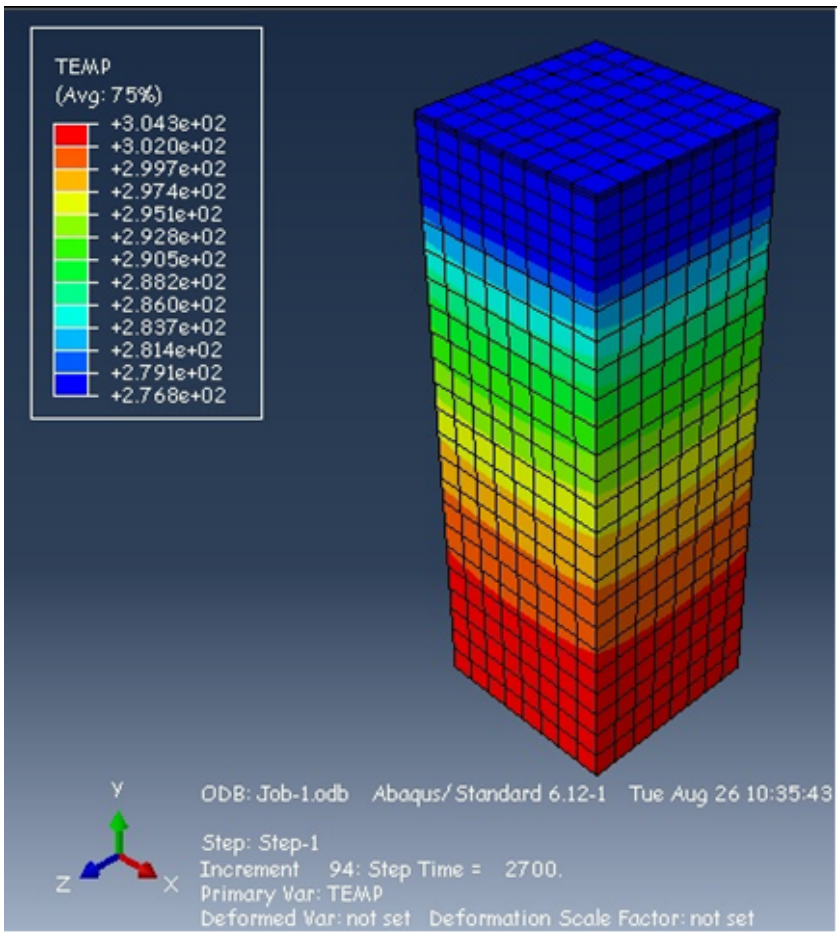

Figure 8. Temperature distribution within tissue following 45 min of cold exposure. Surface temperature was set at 5 °C.

cryolipolysis they reported a decrease in skinfold thickness. At the end of the experiment a 19.7 ± 5.9% decrease was observed in G1 and 28.5 ±5.9% in G2 (10).

This simulation indicates that the lower the applied temperature is, the more temperature decreases in deeper layers. Temperature also decreases more quickly below the normal temperature of the human body when lower temperatures are applied. However, as is evident from our results, cold exposure must be applied within a specified time duration. If heat extraction of the sample oversteps the threshold time it does not result in significant improvements. On the other hand, using low temperatures for longer times may result in irreparable damages.

According to our simulation results one may note that temperature reduction is more considerable for shallow layers below the tissue surface. Comparison of temperature variations at depths of 10 and 28 mm reveals that temperature reduction is more intense in shallower depths (Figures 3–6). Changes in deeper layers of tissue are not very notable and these changes take place more slowly.

The efficacy of cryolipolysis has been proven for reduction of excess body fat. As was mentioned above, cold exposure of a tissue surface for up to 20–30 min will result in significant improvement in fat reduction procedure. Findings of our simulation indicate sufficient temperature reduction, enough to achieve the desired cryogenic effects. We think that simulation of the mechanisms governing therapeutic operations contributes significantly in enhancing the procedures. However, numerous studies are needed for the effective and safe performance of these operations.

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