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Fabrication methods of phantoms simulating optical and thermal properties

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Abstract

The objective of this paper is to present fabrication methods of phantoms that simulate optical and thermal properties for different human tissues. This kind of phantom is very helpful for many biomedical research applications. For instance, it may be utilized in photothermal therapy of cancer. Therefore, it is intended to simulate optical properties in NIR (near infrared) range since this kind of therapy operates at this section of the spectrum. The existence of such phantoms is quite practical and useful once they replace real tissues. It has been utilized two materials to fabricate the phantoms: polyvinyl chloride-plastisol (PVC-P) and agar gel. In order to yield the different properties of each type of tissue, it is purposed to make layers of phantoms to reach this goal.

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Keywords: phantom; optical and thermal properties; muscle; fat; hyperthermia.

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1. Introduction

Massive investments in research in the treatment of cancer have been applied in various fields of human knowledge, contemplating the Medicine, Physiotherapy, Biomedical Engineering and related areas. There are, already, several types of treatments; one of them is the hyperthermia, which consists of heating the tumor region by electromagnetic radiation in the near infrared range. This type of treatment is not yet fully effective due to the lesion of healthy tissues affected by the radiation.

Given the importance and the cause of such studies, there is a need for materials that simulate adequately optical and thermal properties of human tissues. It is possible to utilize real tissues directly in experiments. However, the use of phantoms is a reasonable alternative and may replace, with benefits, the application of real tissues. The designation "phantom" refers to any apparatus or material that mimics operation or physical properties of human systems or tissues. It allows systematic testing and optimization of new methodologies in a controlled way, before testing on animals or humans.

In this sense, the use of phantoms simulating optical and thermal properties of tissues such as muscle and fat is of great interest. Such thermal properties are thermal conductivity and specific heat and the optical property is the transmittance in a range of wavelengths.

Therefore, the method of manufacture of these materials must be standardized in order to achieve regularity in their properties. The objective of this work is to present a functional method of manufacture that allows reaching the described proposal.

1.1. Advantages of using phantoms

The use of phantoms is recurrent in several studies in the field of Biomedical Engineering and the reason of this is the great convenience brought by this feature, allowing simulating, with different levels of complexity, systems or human tissues. In the case of projects related to hyperthermia treatment of cancer, the use of phantoms is very timely.

The advantages of using this device involve factors like cost, convenience, availability of material, storage (conservation), cooking time, life cycle, toxicity, easy handling and good reproducibility. Therefore, the use of phantoms in place of biological material is an effective alternative in initial tests of research in the mentioned area (hyperthermia).

Thus, when the initial phase of research already has shown positive results with phantoms, it is necessary to use the real tissue which was mimicked by the phantom in order to revalidate the obtained conclusions. In general, lab rats are a plausible alternative. In the last instance, having presented satisfactory results, the tests of studies can be applied to people.

However, it is necessary to choose materials that, in addition to meet the conditions have optical and thermal properties close to that's of muscle and fat. The choice of these materials is based on preliminary results and has led to two options: PVC-P and Agar gel. Both have advantages and disadvantages in certain aspects but serve well the imposed conditions. The following table illustrates the comparison between the attributes of the two materials.

Table 1. Attributes of the materials

Factors	PVC-P	Agar gel
Cost	Average	Cheap
Availability	Easy	Easy
Handling	Easy	Average
Life cycle	Long	Short
Reproductibility	Good	Average
Toxicity	No toxic	No toxic

1.2. Specifications of PVC-P

The PVC-P is a polymer used as raw material for phantoms and simulates well the optical and thermal properties of tissues in the range of near-infrared (NIR), that is, from 1300 to 2300 nm. In addition, its practicality is an important decision factor, since its manufacture is uncomplicated. Besides, it does not require conditions of conservation, making the handling simple and, also, has a long life cycle.

1.3. Specifications of Agar powder

Agar is a bacteriological powder that, when dissolved in water, remains in a gelatinous state in ambient temperature after being cooked. One of the biggest advantages of this material is its cost, being approximately 0.6 €/L, while the price of PVC-P is around 14.6 €/L. The biggest disadvantage, on the other hand, is the handling of these phantoms, because they dehydrate rapidly and have a short life cycle: one week at the most.

1.4. Addition of NaCl

In phantoms of Agar gel, it was also added a concentration of NaCl. The purpose for this is to keep the optical property of the phantom unchanged, but changing their thermal characteristics, with the aim of obtaining results similar to those of the muscle tissue. In the case of PVC-P, due to its no-polarity, the mixture does not lead to good results, becoming the phantom extremely fragile and, then, with the handling compromised. The Agar gel, however, has a large amount of water in its composition, allowing the solubility of the salt.

The use of PVC-P proved to be effective for simulation of fat while the use of Agar gel is suitable to simulate muscle. For this reason, the two materials are of interest and the method of fabrication of each one of them has been developed.

2. Fabrication methods

The existence of a standard method for fabrication of phantoms is essential to ensure that the production depends on the minimum possible of the handling of who prepares them. The method of each material is described in the items below.

The reason for dealing with two different materials lies in the fact that the Agar gel simulates well the optical and thermal properties of muscle tissue and the PVC-P, in turn, mimics fat properties. It is possible to combine these two types of phantoms in order to obtain a multi-layer phantom of fat and muscle, allowing a more detailed simulation of the constitution of human tissues.

2.1. Method for PVC-P

Fig. 1. A bottle of PVC-P.

- Sample of 300 ml of PVC-P is placed in a Becher

- The sample must be placed in a vacuum chamber for approximately 1 hour to prevent formation of trapped air bubbles
- The Becher with PVC-P must be placed in an oven pre-heated between 170°C to 180°C and stay at this temperature for 1 hour
- The coloration of PVC-P should be yellow when it is removed from the oven
- The sample with PVC-P is carefully poured into convenient molds, avoiding the formation of bubbles
- A glass plate must close the upper surface of the mold in order to yield a straight and flat surface
- After 5 minutes in this configuration, the plate can be removed and the phantoms must be solidified in the mold, from where they can be removed manually

2.2. Method for Agar gel

Fig. 2. Agar powder.

- 300 ml of distilled water is placed in a Becher
- 15.6 g of powder of Agar is added to the Becher, producing a concentration of 52 g/l
- The additional quantity of NaCl, if it is the case, is also added (100 and 200 g/l)
- The mixture is blended continuously by a magnetic stirrer for 10 minutes
- The mixture must be placed in a vacuum chamber for approximately 1 hour
- The Becher with the mixture must be taken to the oven pre-heated between 70°C and 75°C and stay during 4h approximately
- The mixture is carefully poured into convenient molds, avoiding the formation of bubbles
- A glass plate must close the upper surface of the mold in order to yield a straight and flat surface
- After 5 minutes in this configuration, the plate can be removed
- After 20 minutes, the phantoms can be removed manually from molds and placed in aqueous solution (in the case of phantom pure Agar) or in saline solution with the same concentration of the phantoms
- The containers where the phantoms will be stored must be closed in order to prevent evaporation of the water

3. Measurements of optical and thermal properties

It was made use of two methods to measure thermal conductivity of the phantoms. The Flash method was utilized for the PVC-P phantoms. Given the constitution of the Agar gel phantoms, it was not possible to apply this method. Instead, the linear probe was used. For both phantoms, the Differential Scanning Calorimeter (DSC) method was applied to determine the specific heat.

In the Flash method, it is necessary to know the density of the samples. Therefore, the measurements were made in a densimeter.

The optical behavior was evaluated by making a spectroscopy of the both types of phantoms. The results of this measurement relate the transmittance of light with the wavelength irradiated.

3.1. Flash method and DSC

The thermal diffusivities, densities and specific heats of the produced phantoms were respectively measured with the NETZSCH LFA 447 NanoFlash, with a Sartorius YDK 01 densimeter mounted on a Marte AM 220 scale and with a Differential Scanning Calorimeter NETZSCH - DSC 204 F1 Phoenix.

3.2. Linear probe

The probe Hukseflux TP02 consists of a tube (needle) of stainless steel of 150 mm long and 1.5 mm of external diameter also connected to a base of stainless steel with 50 mm length and 10 mm of external diameter. At the base it can be found a temperature sensor PT-1000 for the measurement of the joint temperature of the thermocouples and can be used for measuring the actual temperature of the probe and the medium. In the base of the probe there is a cable connection of temperature sensors and electrical resistance. The probe TP02 is indicated for identification of thermal conductivity of granular soils, pastes, viscous fluid materials, with a thermal conductivity of 0.16 W/mK. For measuring the thermal conductivity of the phantom, the probe was fully inserted in the middle of the sample so completely enveloped its phantom heated region. To this end, the beam must be at least 40 mm, the applied voltage must be of at most 3 V and the expected uncertainty in the measurements is ± (3% +0.02) 1oK W/mK. In the case of the probe laboratory, electrical resistance per unit length of the probe is 75.72 Ω / m.

3.3. Spectroscopy

The absorption coefficients, at wavelengths ranging from 1300 to 2300 nm, were measured with the spectrophotometer UV-VIS, available at IMA (Macromolecules Institute, UFRJ).

4. Results

4.1. Thermal properties

Following results show the results obtained of thermal conductivity and specific heat. It is possible to note that the values of thermal conductivity of the Agar gel phantom with 200 g/l of NaCl and of the muscle are very close. However, the value of specific heat of muscle is closer of the phantom with 100 g/l of NaCl.

PVC-P results show that its thermal conductivity is much closer of the fat than that of Agar gel.

Table 2. Thermal properties of PVC-P.

Density (kg/m³)	Thermal diffusivity (mm²/s)	Specific heat (J/gK)	Thermal conductivity (W/mK)
995.1±0.1	0.087±0.003	1.79± 0.01	0.150±0.004

Table 3. Thermal properties of Agar gel (52 g/l).

Phantom	Thermal conductivity (W/mK)	Specific heat (J/gK)
Pure	0.48±0.02	4.63±0.05
100 g/l NaCl	0.49±0.02	3.96±0.04
200 g/l NaCl	0.52±0.03	4.40±0.04

Table 4. Thermal properties of tissues.

Tissue	Thermal conductivity (W/mK)	Specific heat (J/gK)
Fat	0.203	2.678
Muscle	0.529	3.684

4.2. Optical properties

Following results show the behavior of the absorption coefficient of phantoms made of PVC-P and Agar gel compared with muscle and fat.

There is a similarity between PVC-P and fat in the range 1300 nm to 1600 nm, as well as the muscle in the range 1300nm to 1400 nm. Likewise, the value of the absorption coefficient of Agar gel in 800 nm is very close of the one of the muscle.

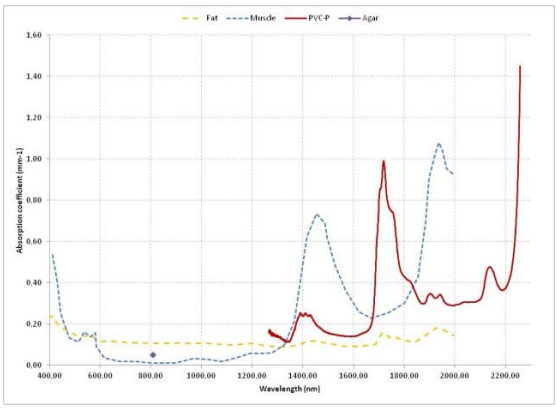

Fig. 3. Absorption coefficient of phantoms and tissues.

4.3. Effect of NaCl

The expecting effect of the addition of NaCl in Agar gel phantoms is to maintain its optical properties by changing its thermal properties. Qualitative results were obtained for absorbance of Agar gel phantoms (pure and with 100 g/l of NaCl).

As shown in Fig. 2, the curves of absorbance have the same behavior through the wavelengths, except for a vertical translation. On the other hand, as shown in Fig. 3, there are small differences in thermal conductivity for different concentrations of NaCl.

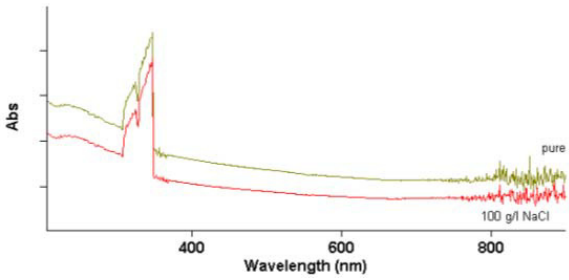

Fig. 4. Absorbance of Agar gel phantoms pure and loaded with NaCl.

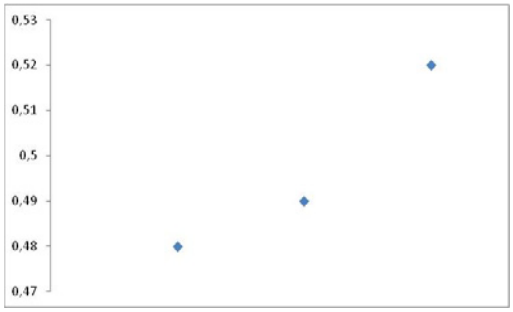

Fig. 5. Increase of thermal conductivity with concentration of NaCl. From left to right: pure, 100 g/l and 200 g/l of NaCl.

5. Conclusions

The obtained results show that, for the applied concentration of agar and for the described procedure of fabrication of both phantoms, the optical and thermal properties of phantoms made of Agar gel are next to the muscle properties, as well as the behavior of the phantoms made of PVC-P is similar of that of the fat.

The addition of NaCl yielded a bit difference in thermal conductivity of the phantom but its behavior of optical absorbance remained the same. It shows that it is possible to change thermal conductivity by maintaining the same optical behavior.

By having this recipe of fabrication of this type of phantom, it is possible to make multi-layer phantoms, which are constituted of a layer of Agar gel and another layer of PVC-P, simulating the configuration of human tissues. Furthermore, it is also possible to create phantoms with different quantities of material, concentration of Agar powder and NaCl, time of cooking as well as other salts in place of NaCl. Different combinations of these factors may lead to a more effective method, which may be faster and spend less material.

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