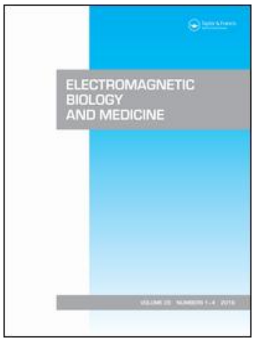

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Influence of electrodes on the 448 kHz electric currents created by radiofrequency: A finite element study

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ABSTRACT
Radiofrequency is a technology used in physical rehabilitation by physicians and physiotherapists for more than fifteen years, although there exist doubts on how it works. Indiba is a particular method that applies a voltage difference of 448 KHz between two electrodes, creating an electric current between them. These electrodes are an active one that is placed on different areas of the body and a passive one that is left on the same position during the treatment. There are two different types of active electrodes: the capacitive one and the resistive one. In this paper, it has been studied how the different electrodes affect the current density inside the body and thus how they affect the efficacy of the treatment. It shows how finite element calculations should help physicians in order to better understand its behavior and improve the treatments.

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KEYWORDS
Radiofrequency; therapy; electrodes; electric current density

Introduction

Radiofrequency is a well-known technology that has been used by physicians and physiotherapists for more than fifteen years (Trillo et al., 2000; Takahashi et al., 1999; Takahashi et al., 2000; Vicent, 2005). Indiba® is one of the treatments that uses radiofrequency. It is based on a device that applies a 448 KHz electric current that flows when a voltage difference is created through the body between two electrodes placed in diverse areas of the human body. During the treatments, two kinds of electrodes are used: an active one that can be managed by the therapist and a passive one. The passive electrode is always a rectangular stainless steel plate of 20 × 25 cm^2. It remains at the same place throughout the treatment process, and it is ground connected, thus acting like a returning electrode. The active electrode may have different sizes and materials. The active electrode has a circular shape, with diameters ranging from 20 to 65mm. Moreover the active electrode is divided into two different groups: the resistive one and the capacitive one. The material of the resistive electrode is stainless steel, which is the material applied in direct contact to the body, while the capacitive one is a metallic electrode coated with a 2 mm layer of a polyamide, which is the material applied to the patient. The active electrode can be moved during the treatment and is the one that creates the stimulating electric voltage.

Finite element calculations are widely used for computing electric currents inside the human body (Dimbylow, 2005; Dawson and Stuchly, 1998; Gandhi and Kang, 2001). A commercial finite element program called COMSOL has been used for these calculations. The electric currents module is the one that fits these calculations. In this work, we have studied, using finite elements calculations, how different electrodes affect the electric currents created in a geometric illustration that contains the main tissues that can be found in a physiotherapy treatment. Both the size and type of electrodes have been studied. The purpose of this work is to show how finite element calculations may help physicians in order to improve the quality of the treatments.

Simulation method

In Figure 1, it can be seen the geometry used in the calculations. This geometry has been selected in order to see how the electric current lines behave inside the different organs and tissues and in their interfaces. Although for each treatment and patient, the dimensions are different, this geometric illustration helps to indicate qualitatively how the currents would be distributed in real treatments. The size of each tissue is shown in Table 1. The two Indiba® electrodes were

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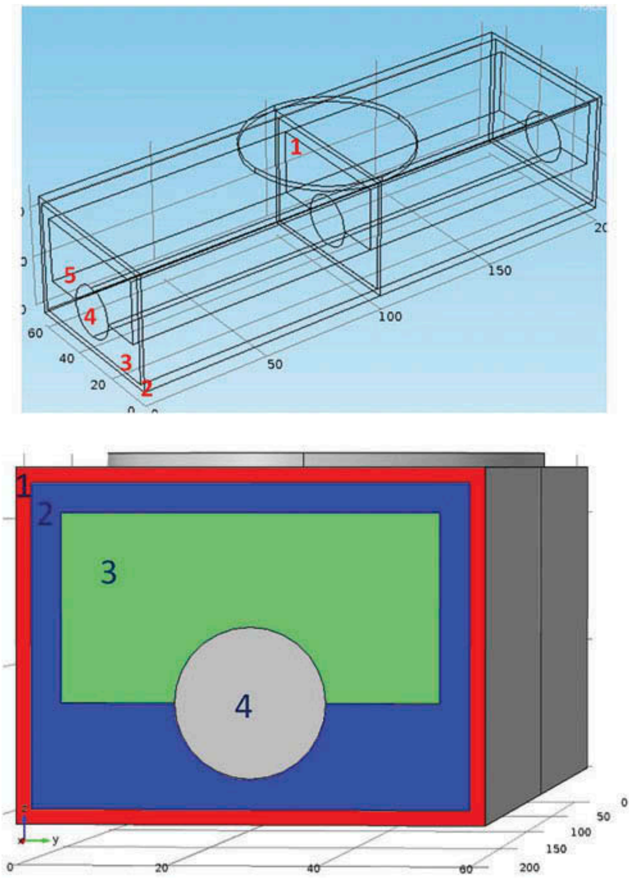


Figure 1. Geometry used in the numerical simulations for the transversal mode. Region 1 is the active electrode for the transversal simulations. Region 2 has the physical properties of skin. Region 3 has the physical properties of fat. Region 4 has the physical properties of bone, and region 5 has the physical properties of muscle.

Table 1. Dielectric properties of organs.

Organ	Conductivity (S/m)	Relative permitivitty	Thickness (mm)
Muscle	0.44	4000	25
Skin	0.1	4000	2
Bone	0.02	180	10 (radius)
Fat	0.025	37	4 top

simulated at geometrical opposite sides of the illustration, which consists in regions that have the dielectrical properties of muscle, bone and skin at 448 KHz. These properties are shown in Table 1, and they were taken from the work of Gabriel et al. (1996, http://niremf.ifac.cnr.it/tissprop/htmlclie/htmlclie.php).

Two main situations were simulated. In the first one (transversal mode), the active electrode was placed on the middle of the longer side, while the passive electrode was placed on the opposite side, occupying all the lower side of the geometry, as it is shown in Figure 1. In the second one (longitudinal mode), the electrodes were placed on the middle of the shorter sides, the active one being placed in front of the passive one, as it is shown in Figure 2. In the transversal position, the cross section is greater than the distance between the electrodes, while in the longitudinal one, the distance between electrodes is the bigger one. In the longitudinal model, two new sections, having the properties of skin and fat, have been inserted at each extreme in order to simulate the proper contact between the electrodes and the skin.

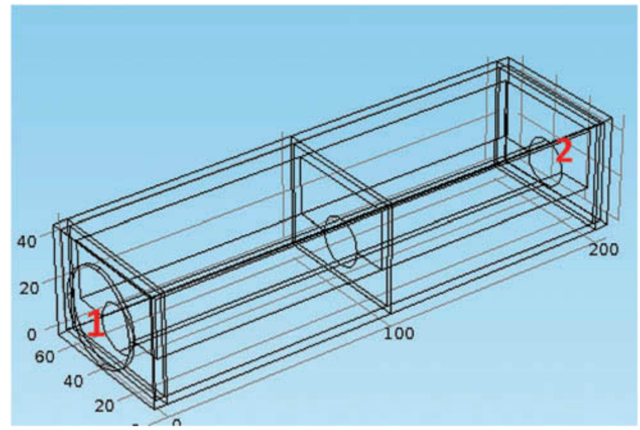


Figure 2. Placing of the electrodes as used in the numerical simulations for the longitudinal mode. Region 1 is the active electrode for the longitudinal simulations. Region 2 is the returning electrode.

The method followed for the calculations was as follows:

A voltage difference was introduced between the electrodes. This voltage difference creates an electric current in the conducting materials that are placed between them. COMSOL allows studying both the electric current lines distribution in the tissues and the total electric current that flows through the electrodes. We have compared these results for different types and sizes of electrodes. The voltage difference used for all the calculations was 10 V. For these calculations, the frequency domain for the electric currents module was used, in which COMSOL imposes that all the electromagnetic fields under study have the same frequency, which in this work has been set at 448 kHz. For all the elements of the geometry, a predefined “finer” size was used for the mesh.

Results

The current lines distribution for three different diameters (23, 40 and 65 mm) of the resistive electrode placed in the transversal mode is shown in Figures 3–5. Two different cross sections are portrayed for each electrode.

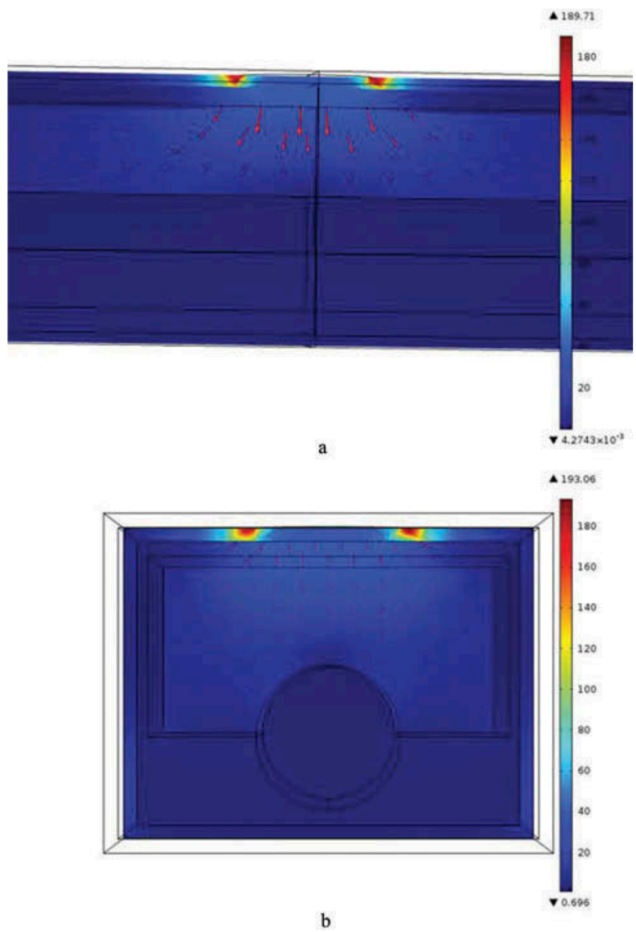


Figure 3. Electric current lines distribution for 23 mm resistive electrode in the transversal mode; a) xz plane; b) yz plane.

In order to have a clearer sight of the current density distribution, its value across five lines has been studied. The lines are shown in Figure 6. The lines cover the geometry longitudinally. Line 1 is 0.5 mm from the active electrode, lines 2, 3 and 4 are placed at the middle of the fat, muscle and bone area, respectively, and line 5 is 0.5 mm above the passive electrode. These lines have been selected in order to see how the current density behaves inside each organ.

The previously observed results of Figures 3–5 can be analyzed in Figure 7, where the value of the current density along lines 1–5 is shown. The values of the conduction and displacement components of the total current that flow through the three active electrodes are shown in Table 2. Again, as expected, the total electric current is higher for the greatest electrode, since the impedance decreases as the cross-sectional area increases. But this decrease is not inversely proportional to the section of the electrode. Thus, the current density at the electrode is much bigger when the electrode is smaller.

Also, the conduction current, due to the conductivity of the organs (the one in phase with the applied voltage difference), is around five times bigger than the displacement current, due to the permittivity of the organs.

In Figure 8, it is shown the results of the calculation for the 23 and the 65 electrodes when the electrodes are located in the longitudinal direction. Figure 9 shows the current density along the above commented lines. There we can see that the current density for the smaller electrode as we get inside is 30% less than that of the bigger one.

Table 3 shows the total conductive electric current for the three electrodes. The total current for the smaller electrode is around 50% lower than that of the higher one.

For the capacitive electrode, the same study has been performed. In Figure 10, we can see the current lines distribution for the 23 mm diameter capacitive electrode.

Discussion

In Figures 3–5, it can be observed that the shape of the current lines is similar for all the resistive electrodes in the transversal mode. Starting from the active electrode, in the three images, the electric density is bigger at the borders of the electrode. This is due to the skin effect, which diminishes the current as we go into a conductor. It can also be seen that in the proximities of the electrodes the current lines are perpendicular to them, and as they go away from them, they begin to change their direction trying to get the maximum cross section. So, as we go inside the geometry, there is a bigger section of the organs that has an appreciable current density. This current density is more homogeneous than the one closer to the electrode and is bigger at the line joining the middle of the active and the passive electrodes. When we get close to the returning plate, all the current lines are absorbed by the plate. This pattern is repeated for the three different active electrodes, but there are some differences: It can be observed, as expected, that the bigger the active electrode is, the bigger the area that is submitted to an appreciable electric current is. Also it can be seen that the biggest value for the current density is obtained for the smaller electrode, although in a smaller area.

In Figure 7, it can be observed these results more closely. For Line 1, it can be seen that the highest current density appears for the smaller electrode, although again in a smaller area. Also, the skin effect is remarkable. In line 2, the current density is still bigger for the smaller electrode, but the skin effect is less important. But as we go inside the body, at lines 3 and 4, the current density is both bigger and takes place in a wider area for the bigger electrode. The current density is bigger, as expected, for the muscle than

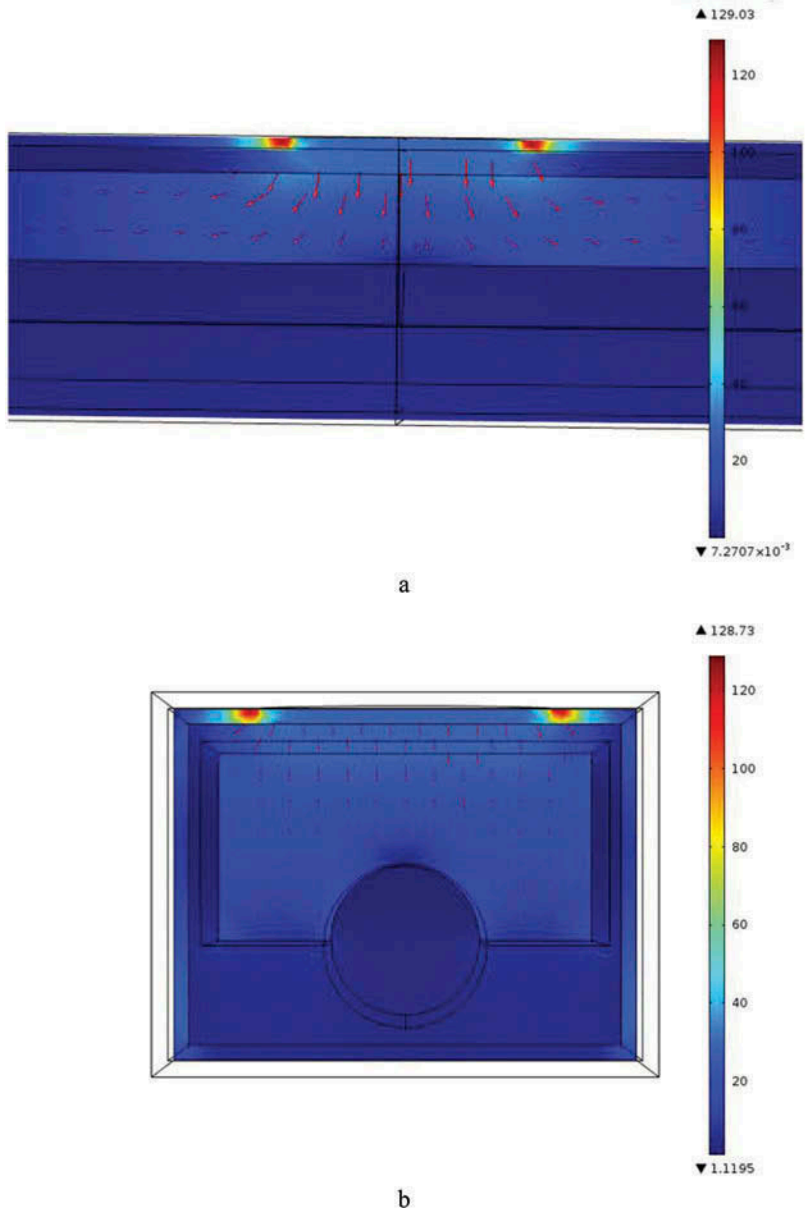


Figure 4. Electric current lines distribution for 40 mm resistive electrode in the transversal mode; a) xz plane; b) yz plane.

for the bone, since its conductivity is higher. In fact, the shape of the current density at the muscle shows that the current lines try to avoid entering the bone, since the electric current has an easier path going through the muscle that surrounds the bone.

As happened in the previous calculations, for the longitudinal calculations, the skin effect creates bigger current density close to the border of the electrodes. But as we go further, the current density lines take the same shape for both electrodes. This behavior could be expected since when the current runs longitudinal to the different organs, they act like resistors connected in parallel, and thus, the electric current is divided into the different organs proportionally to their impedance.

The shape of the current density distribution for the capacitive electrodes is very similar to that of the resistive one, but in this case, the current close to the active electrode is more homogeneous through all the section of the electrode. This is because the dielectric material that covers the electrode does not have such a big skin effect due to its low conductivity. The other main difference is that for the same applied voltage the current density inside the different tissues and bones is two orders of magnitude less than the one created by the resistive electrode. This can be observed in Figure 11, where the current density in lines 1–5 is shown. On the other hand, the relation between the sizes and placing of the capacitive electrode is the same as the one that takes place for the resistive electrodes.

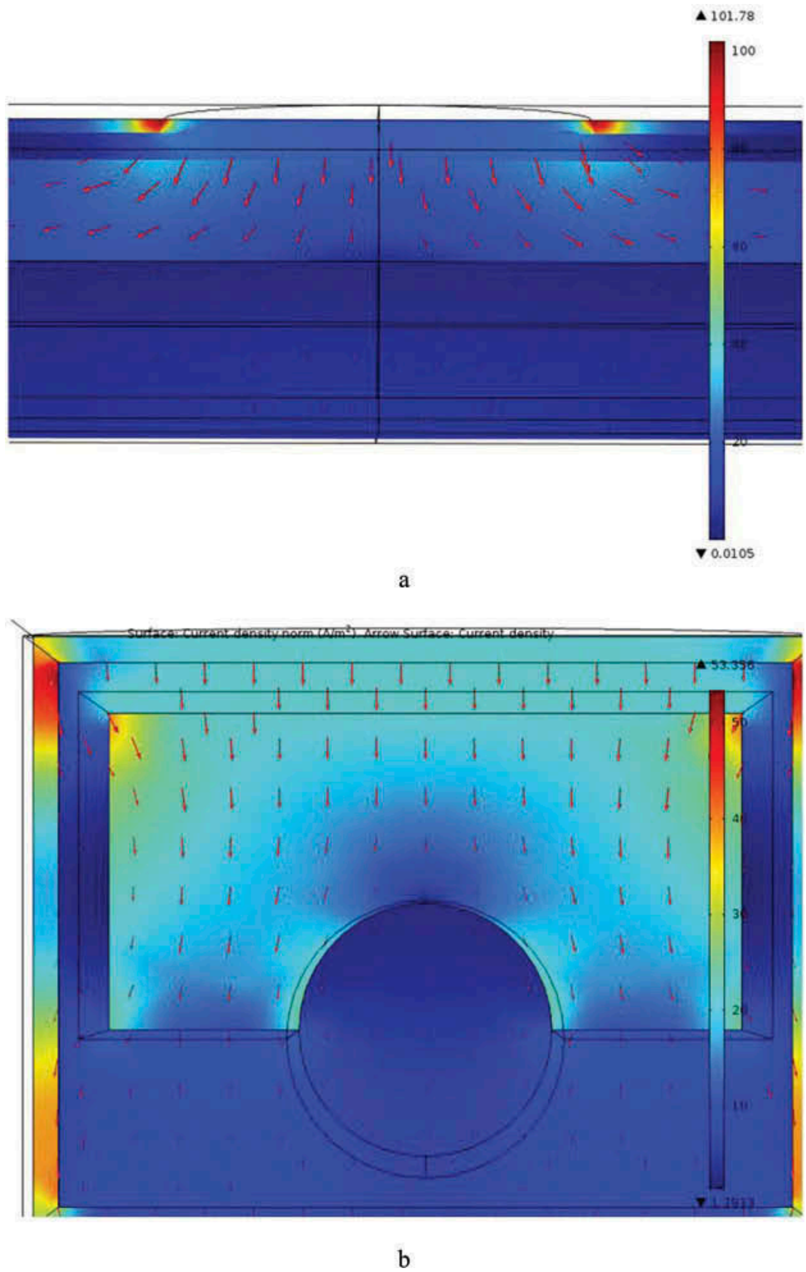


Figure 5. Electric current lines distribution for 65 mm resistive electrode in the transversal mode; a) xz plane; b) yz plane.

Conclusions

The current lines created by Indiba® electrodes depend on the size, type and placing of the electrodes. Also, the influence of the size of the electrodes is related to their placing. When the cross section the current flows by is much bigger than the area of the electrodes and the distance between them (transversal mode), the current density created by the smaller electrode, close to it, is more intense, although in a smaller section. This means that when the electrodes are placed on a patient, the current at the contact surface will affect less area but in a more intense way. As we go inside, the body the current density is bigger for the bigger electrode both in module and in affected area.

When the cross section is smaller than the distance between electrodes, the current density far from the electrodes is almost independent of the size of the electrodes, while closer to the electrodes the current density will be bigger for the smaller electrode. So, inside of the body, the tissues will receive the same amount of energy, while in the outer part of the body, the smaller electrode will have a bigger current density in the skin placed close to it.

The influence of the type of the electrodes is evident near the surface of the electrodes. The resistive one has a

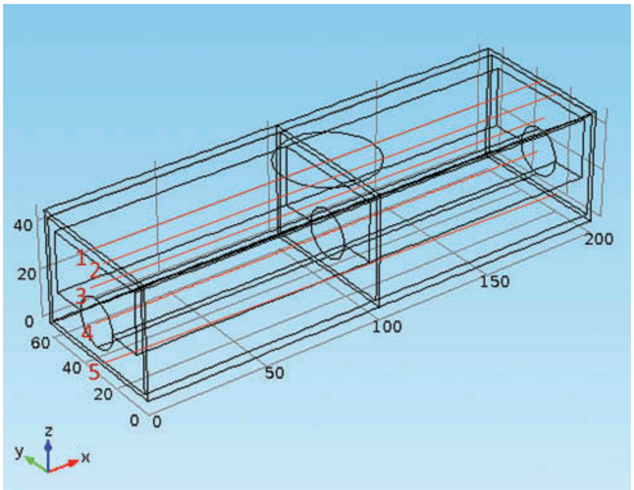


Figure 6. Position, inside the geometry described in Figure 1, of five lines in which the current density has been studied.

Table 2. Conduction and displacement components of the total current flowing by each electrode in the transversal simulation. Average current density.

Diameter of the electrode (mm)	Conduction current (A)	Displacement current (A)	I/section of the electrode (A/m^2)
23	0.026	0.0056	64
40	0.047	0.0092	38
65	0.078	0.0141	23.5

big current density near its border, and it decreases as we get closer to its center, while the capacitive one has a more homogeneous current density throughout all its section. When we move away from the electrodes, the shape of the current lines is similar in both cases. Other important fact is that, as expected, for the same applied voltage, the current density is almost two orders of magnitude smaller for the capacitive electrode than for the resistive one.

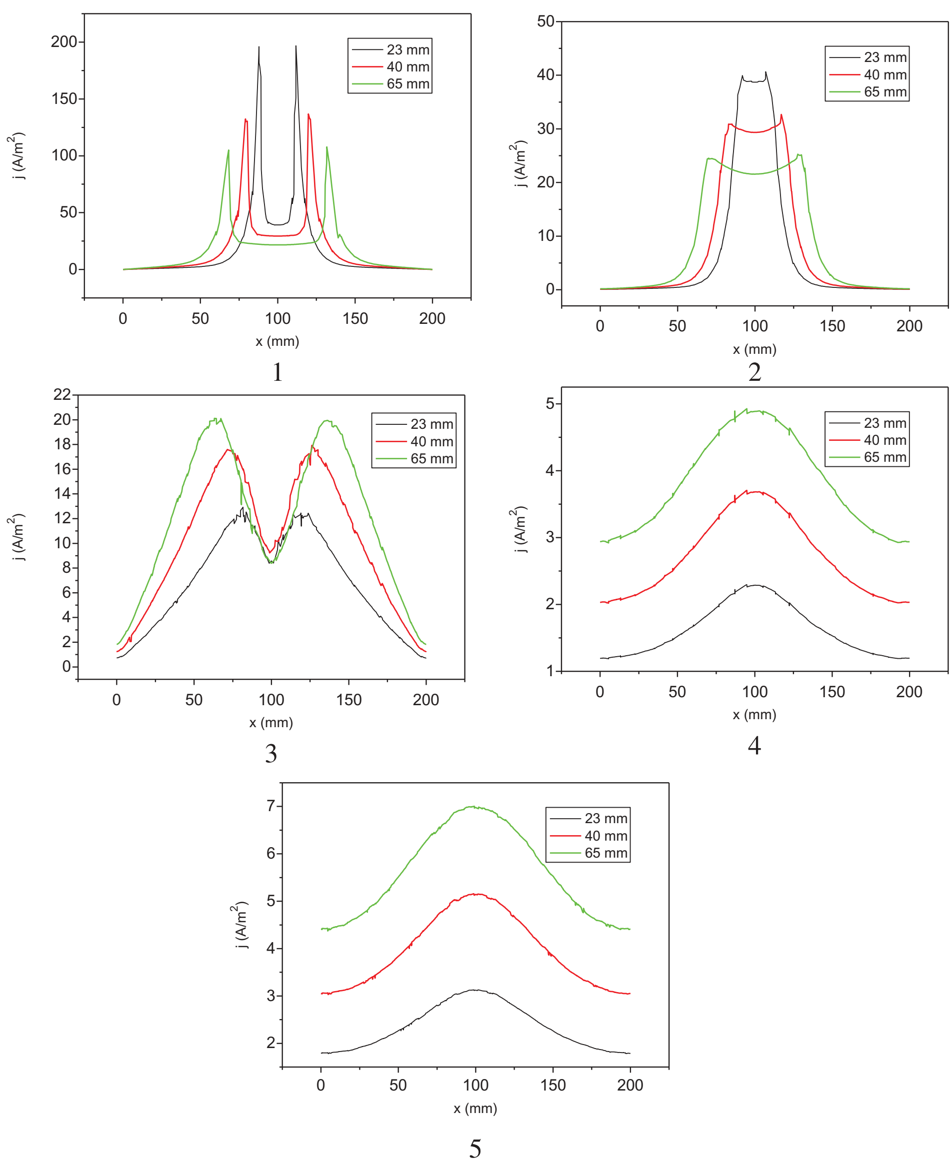


Figure 7. Current density along the lines shown in Figure 6 for the resistive electrodes in the transversal mode.

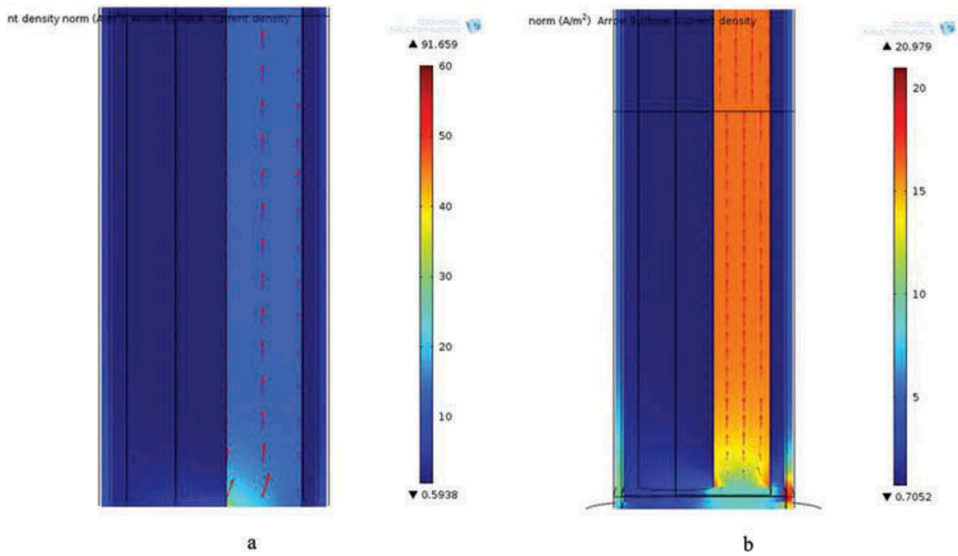


Figure 8. Electric current lines distribution for a) the 23 mm and b) the 65 mm resistive electrodes in the longitudinal mode.

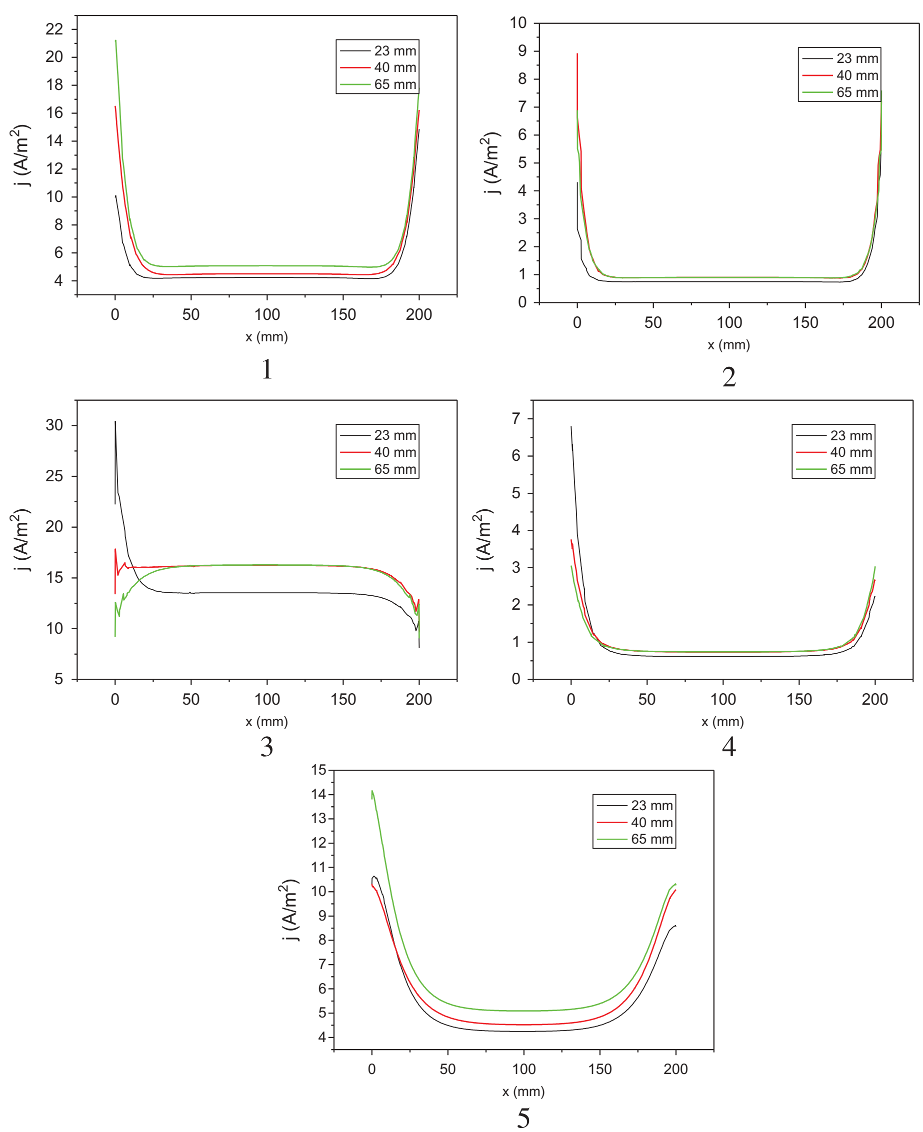


Figure 9. Current density along the lines shown in Figure 6 for the resistive electrodes in the longitudinal mode.

Table 3. Conduction current flowing by each electrode in the longitudinal simulation. Average current density.

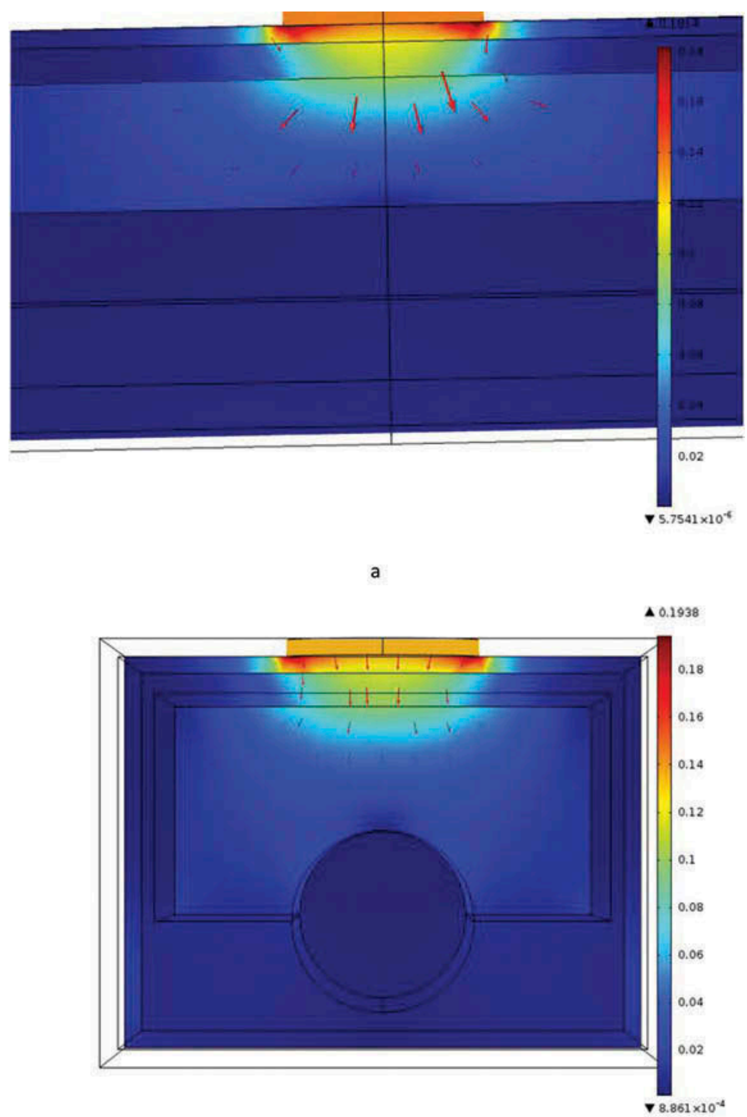
Diameter of the electrode (mm)	Conduction current (A)	I/section of the electrode (A/m^2)
23	0.011	26
40	0.015	12
65	0.019	5.7

The authors of the paper believe that all these differences have to be taken into account for a correct treatment. This work should help physicians when choosing the kind of active electrode for different treatments. For example, when an injury is close to the surface of the body, it should be taken into account the skin effect that appears for the resistive electrode, while for injuries inside the body, it should be taken into account the size of the injury that needs to be treated and the distance from the active electrode. Moreover, this kind of calculations should help to explain why radiofrequency treatments work differently in muscle treatments than in bone treatments.

These results also show how useful this kind of calculations may be in order to improve specific treatments, by performing calculations with the real geometry that can be extracted from MRI images. These studies should provide physicians the exact placing and type of electrode they shall use for each treatment.

Declaration of interest

This work has been performed using a monopole capacitive/resistive 448 KHz radiofrequency device (INDIBA® activ



b

Figure 10. Current density distribution for the 23 mm capacitive electrode in the transversal mode; a) xz plane; b) yz plane.

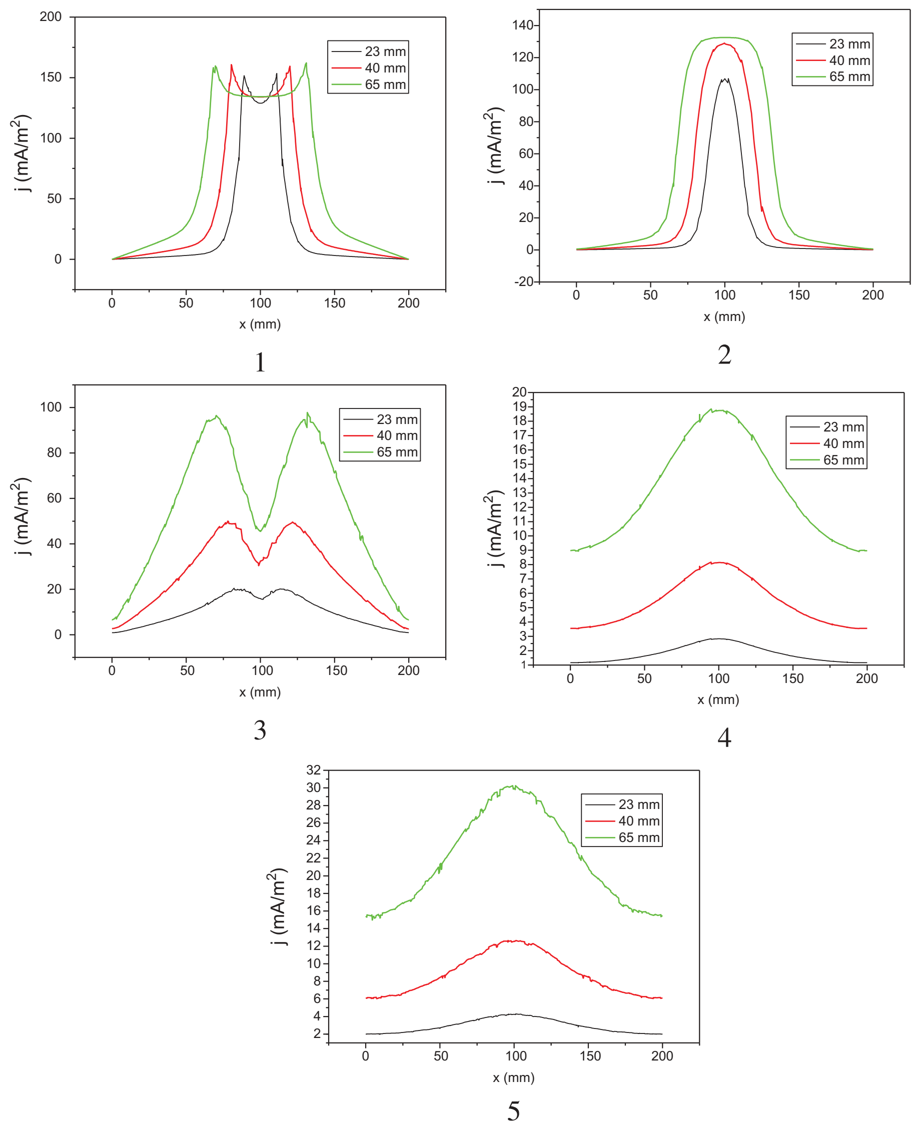


Figure 11. Current density along the lines shown in Figure 6 for the capacitive electrodes in the transversal mode.

therapy; INDIBA S.A. C/Enamorats 1-17, 08013 Barcelona Spain). Nevertheless, there is no conflict of interest since the research has been performed with total economic, execution, conclusion and publication independence.

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