Ablation Applicator for Destructive Hyperthermia Treatment

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Abstract. This work is a preliminary research which is opening a field of examination of this complex clinic method (i.e. treatment using ablation applicators). Although it is established in many medical facilities its effects were not analyzed thoroughly and there are many unknown factors which can affect patients in clinical practice. We aim to bring new analysis methods which can simply and clearly determine how the tissue in the treated area will be affected and we want to inspect and overcome potential risks connected to this medical method.

1. Introduction
Although radiofrequency and microwave ablation is used widely in destructive hyperthermia, its precise effects on patients and a treated area are not well inspected. In this paper we focus on several applicators for radiofrequency hyperthermia (RF hyperthermia) and we analyze them in series of simulations (using SEMCAD X [1] and MATLAB [2] for results processing). Experiments in tissue samples were also conducted.

Radiofrequency ablation usually utilizes frequencies around 500 kHz (in comparison to microwave treatment with frequencies in range of GHz). Two electrodes (active and dispersive) are connected to a patient’s body which closes an electrical circuit and once power is switched on electric currents start flowing through electrodes. Dispersive electrodes (there can be more than one) ensure that the electric current density is considerably lower than in the near vicinity of the active electrode (this is due to large connecting surface of dispersive electrodes to the patient’s body). Electric current flowing through the tissue causes resistive losses which affect mainly the vicinity of an active electrode. These losses generate substantial heat which causes cell death (necrosis). [3]

In this paper we introduce four types of ablation applicators which can be used in practice. We analyze specific absorption rate (SAR) in the simplified model of a human body using SEMCAD simulations. Furthermore we inspect how the SAR distribution is affected when we change distance and position of dispersive electrodes. We also discuss obtained results considering its usage in clinic practice.

2. RF ablation system
The system layout is well shown in Fig. 1. It consists (as mentioned above) of two electrodes (dispersive electrode may have multiple pads), generator of high frequency voltage and additional controlling and measurement systems. Applicator (active electrode) is equipped with a handle for the operator which enables her to steer the tip of the electrode to the designated place for the treatment (CT and MRI results are used to locate the exact position of a tumor) and also (if the type of the electrode allows it) to eject or retract other structures from the inside of an applicator.

In further text electrode types used in this work are described.
2.1. Active electrode
Due to the facts mentioned above an active electrode plays a crucial role in the RF ablation system. Its position (absolute and relative to a dispersive electrode) and shape can affect treatment procedure greatly. It is the reason why we inspect how the energy is absorbed if different electrodes are used or if their position is altered. Only through this careful analysis the best results can be obtained.

2.1.1. A single-tip electrode. A single-tip electrode can be seen in Fig. 2 a). This is the simplest electrode design which can be subsequently upgraded with additional systems (hollow tip with temperature control system – Fig. 2 b) etc.)

2.1.2. An umbrella electrode. Its usual design is shown in Fig. 2 c). Design of an electrode for radiofrequency ablation is restricted by the fact that it has to be inserted inside a patient’s body with as little damage to healthy tissue as possible. This means that all the different electrodes must be retractable back inside its cannula. These limitations lead to designs as shown in Fig. 2 c), d) etc.

2.1.3. A helical electrode. Another design which allows ejecting electrode once a cannula is inside the body is a helical structure, see Fig. 2 d).

Fig. 2 Active electrodes – a) single tip – b) single-tip with temperature control system – c) umbrella – d) helix
2.2. Dispersive electrode
The other end of the system is a dispersive electrode. It can consist of several pads connected (usually using conductive gel) to the surface of a patient’s body. The interface between skin and dispersive electrode has to be large to prevent any significant energy absorption near dispersive electrode (hence the name of the electrode – it disperses the electric current flowing through the treated area).

Dispersive electrodes are usually positioned on thighs where good contact with skin can be assured. Also no vital organs are near in case of any malfunction or unwanted local heating.

3. Models
For purposes of this work we used simulation software SEMCAD X which allows simple modelling. Four models where developed (two different umbrella applicators, one single-tip and one helical applicator). Models of the electrode tips can be seen in Fig. 3.

Supply lines were included in models consisting of a conductive wire wrapped in dielectric isolator and inserted inside cannula. To keep models simple all metallic materials were simulated as PEC (Perfect Electric Conductor with no resistivity), cannula and isolator were simulated as dielectric material with no conductivity.

Model of human body was very simplified because effects of RF hyperthermia are limited to the near vicinity of the active electrode. Simulations with a more complex model of a human body (several organs were simulated with slightly different dielectric parameters) were conducted and no significant differences were found but the time required for a simulation is reduced significantly when the simplified model is used. Whole model for simulations with umbrella electrode with central tip is shown if Fig. 4.
4. Simulations and results
Simulations were done in SEMCAD X and the results were processed using MATLAB. We inspected several things: how SAR differs for each type of electrodes, how SAR is influenced by the distance between active and passive electrodes, how SAR is influenced by a relative position of an active electrode to a dispersive electrode.

4.1. SAR for different types of electrodes
In this part of our work we conducted several simulations with electrodes presented above. It is evident that the surface of an electrode changes peak values greatly (larger an electrode is lower peak values are). That is why we normalized all results to the maximal value which was obtained in the case of a single-tip electrode (single-tip electrode has the smallest surface and thus the electric current density is the highest around it causing the highest losses in tissue). SAR in dB can be seen in Fig. 5.

Fig. 5 SAR in dB around presented electrodes / top 3 – umbrella / second 3 – single-tip / third 3 – umbrella with central tip / bottom 3 - helical
From the results above it is evident that the energy is absorbed only very near to the electrodes. It can be also clearly seen that electrodes with larger surface reach lower SAR levels since currents flowing through nearby tissue distributed to larger volume. Specifically (single-tip electrode has maximum of SAR at 0 dB) SAR maximum is in case of umbrella electrode around -12 dB, in case of umbrella electrode with central tip it is around -4 dB and in case of helical electrode it is around -1.1 dB.

It is clear that in case of a single-tip electrode the effect of RF ablation is the most localized but can cause serious tissue damage if critical values of SAR are exceeded (intensive pain can occur in some cases [4]).

Usage of telescopic electrodes (i.e. umbrella, helical and other types) can prove to be problematic because, as seen especially in the case of helical electrode in Fig. 5, absorbed energy can be distributed mainly around the outer surface of the whole electrode causing some ‘cold spots’ inside the treated area [5]. This fact needs to be looked into since uneven treatment could cause regressions. Proper electrode design is, as mentioned above, unfortunately limited by the requirement of retractive electrode tips into a cannula.

4.2. Effects of various distance of electrodes
In this part of our work we wanted to find out how to augment SAR near the active electrode by moving dispersive electrodes (changing their distance to the active electrode). Fig. 6 depicts how the exposure changes when different distances are introduced to the system. As we can see in the left picture, absorbed energy is much higher if the electrodes are near each other. This can prove to provide much better results during a treatment procedure. On the other hand patient’s safety must be considered and extremely high localized heating effects can cause excessive damage. Also peak values can appear on the edges of dispersive electrodes causing damage to the skin of a patient. According to our preliminary simulations current density is around ten times higher (+10 dB) and is still in safety zone but thorough testing would be required.

Fig. 6 SAR [dB] when (LEFT) dispersive electrodes were near the active electrode (distance around 10 cm) and (RIGHT) dispersive electrodes were far from the active electrode (distance around 30 cm)

4.3. Relative position – effect
Since the energy is primarily absorbed in very near vicinity of an active electrode and treatment effect is protruding through the tissue mainly by heat transfer we concluded (based on our simulations) that rotation of an active electrode does not affects treatment noticeably.

Results of our simulations for three different positions of an electrode are shown in Fig. 7. It is evident that the overall area of the treatment would be rather same in all cases (only rotated accordingly) thus allowing operator to choose the best position fitting particular tumor shape.
Fig. 7 SAR [dB] for three different orientations of an active electrode – from the left – 0°, 45° and 90°

5. Conclusion

From this work on RF ablation we conclude that there is very wide space for further research into the shape of active electrodes and possible unharmful positions of dispersive electrodes which would augment the efficiency of a treatment.

RF ablation is designed especially for small tumor treatment in the places that can be reached with difficulty by conventional methods or where standard procedures would pose too great risk (concerning heart, liver etc.). New and better telescopic electrodes can help overcome this limitation and expand area of the effective treatment and in some cases prevent excessive damage to the tissue.

In further development new designs of active electrodes should be presented. Their design will combine all the requirements (i.e. safety, retractable electrodes, as even as possible SAR etc.) while causing their strict specialization for various tumor types and shapes. Multiple advanced systems may be used [6].

References

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