The effect of eddy currents on magnetic nanoparticle hyperthermia

Cancer is one of the major causes of death worldwide. As of the writing of this thesis, the conventional methods of treatment that are used such as radiotherapy, surgery and chemotherapy have many limitations. These limitations mainly concern the difficulty of localizing the treatment in the affected area. Magnetic hyperthermia is a modern type of treatment, that aims to locally destroy the cancerous tumor. Magnetic nanoparticles can be driven by a magnetic field or injected to the target area. With the application of an alternating magnetic field, the nanoparticles locally increase the temperature and destroy or reduce the cancerous tissues.

However, one of the restrictions that inhibits the clinical application of magnetic hyperthermia therapy is the appearance of eddy currents on healthy human tissues due to the electric field induced by the alternating magnetic field. The appearance of these currents heats healthy tissues, causing adverse side effects in patients and thus prevents the use of higher magnetic fields by limiting the effectiveness of the treatment.

The purpose of this work is to minimize undesired heating due to eddy currents and to maintain a satisfactory heat release from magnetic nanoparticles that could increase the effectiveness of the treatment. To achieve this goal an intermittently applied alternating magnetic field was used (ON-OFFs), instead of a continuously applied one, so that while the field is not applied the healthy tissue can be partially cooled, so that the undesirable temperature increase due to eddy currents is limited.

In this work, solutions mimicking the cancerous tumor area and solutions mimicking the healthy tissues area were studied. Initially, preliminary experiments were carried out to determine the optimal parameters such as the duration of the experiments, the measurements area and the solution homogeneity. Afterwards, there was a series of experiments in a discontinuous alternating magnetic field. In this section, the operating time, the operating cycle and different values of the magnetic field amplitude were studied, and the optimal conditions were determined. The best conditions were those were a lower temperature rise due to eddy currents was witnessed, while a high enough temperature due to magnetic nanoparticles was maintained, in order to achieve an effective treatment.

Subsequently, these optimal conditions were used in ex vivo experiments. In these experiments minced beef meat solutions were used together with magnetic nanoparticles to simulate cancerous tumors while minced beef solutions without nanoparticles were used to simulate healthy tissues. In addition, two different concentrations of nanoparticles (4 mg/ml and 8 mg/ml) were tested in this study. The concentration of 8 mg/ml gave better results.

Finally, two systems that resembled the area of the cancerous tumor and the nearby healthy tissues were studied. The first one was an ex vivo system of minced meat with

MNPs surrounded by minced meat without MNPs that gave results in good agreement with the previous experiments. The second one was system of agarose with MNPs surrounded by agarose without MNPs, where heat transfer was observed from the area with MNPs (mimicking the area of treatment) to an area without MNPs (mimicking adjacent healthy tissues).

Apart from the experimental study, the theoretical, computational models that were created for the experiments are also presented. Theoretical models and experimental results are in good agreement.

This work highlights the effectiveness of using an intermittently applied alternating magnetic field in the treatment of cancer with magnetic hyperthermia and this was observed in experiments on agarose and in ex vivo experiments that were performed. From all the studies mentioned above, the optimal conditions that can lead to eddy current effect reduction and to the maintenance of satisfactory temperatures due to nanoparticles, in order to apply the treatment, were found. These conditions are satisfactory not only for the agarose experiments but also for the ex vivo experiments.

The results of this project are encouraging for the prospect of effectively applying magnetic hyperthermia in the treatment of cancer and protecting the patient from adverse side effects.