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Spin resonance excitation of Gd-based contrast agents for thermal energy deposition

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ABSTRACT

The theoretical and experimental investigation of electron spin-resonance relaxation to deposit thermal energy into liquid gadolinium-based contrast agents for cancer hyperthermia treatment is presented. Previous works suggest that using protons in water are inadequate, with a thermal deposition rate of approximately 1 °C per two years. A novel component of this research relies on the use of gadolinium-chelated molecules, which are currently used as contrast agents in clinical MRI scans. The chelating agents, or ligands, investigated are Gadobenate (MultiHance®), Gadopentetate (Magnevist®), Gadoterate (Dotarem®) and Gadoteridol (ProHance®). The gadolinium atom has seven unpaired electrons in its inner f shell orbital and as a result has a 660 times stronger paramagnetic response when placed in an external magnetic field. The research tests the hypothesis that by using an appropriate external homogeneous DC magnetic field, together with a radiofrequency excited resonator, that a measurable amount of thermal energy is deposited into a liquid gadolinium-based contrast agent. The aim of this research is to ultimately discover a new cancer hyperthermia treatment. The research theory suggests that a temperature rate of 13.4 $°C \cdot s^{-1}$ can be achieved using the gadolinium-based contrast agents under certain experimental conditions, and a maximum of 29.4 $°C \cdot s^{-1}$ under more optimal conditions. The temperature rates are calculated using parameter values commonly found in literature and practice. The simulation and design of the DC magnetic field coil system is discussed, together with the simulation results and design parameters of the radiofrequency loop-gap resonator. The experimental results and analysis indicate that the selected contrast agents have varied responses based on their chemical nature and that only two out of the four contrast agents, Dotarem and ProHance, show a measurable effect albeit sufficiently small that statistical techniques were necessary to distinguish the effect from background. A model fit to the data is performed in order to determine the spin-lattice relaxation time of the contrast agents under the specified experimental conditions. The model estimate is significantly smaller than the values found in literature under similar conditions, with a spin-lattice relaxation time τ_{1e} of approximately 0.2 ps compared to the literature value of 0.1 ns. Although the observed electron spin resonance heating rate is in the milli-Watt range it is still notably larger (167 000 times) compared to the heating rate obtained using protons. The low temperature rates suggest that a more suitable agent or molecule with a larger spin-relaxation time be used, in order to achieve clinical useful temperature rates in the range of 14 $°C \cdot s^{-1}$.