Design and Optimization of Radio-Frequency (RF) Ablation Probes for Pain Therapy

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Chronic back pain results most frequently from degenerative osteoarthritis of the joints of the vertebra, called the facet joints, where much of the movement of the spine occurs. When conservative therapy fails, a commonly performed procedure is radio-frequency (RF) ablation of the nerve supply to the affected facet joints. This procedure involves the use of RF ablation probes that can be inserted into the tissue surrounding the targeted area. Commercially available probe designs are akin to sharp needles, expected to create large field intensities at their tip (E. R. Cosman, Jr. and E. R. Cosman, Sr., Pain Medicine, vol. 6, no. 6, 2005). However, these knife-edge probes do not offer much control over the induced temperature profile ("RF lesion"). Hence, this procedure is accompanied by a high risk of damaging the surrounding tissue, including motor nerves.

We systematically revisit the design of RF ablation probes by associating their surface currents to the induced temperature profile in the surrounding tissue through a multi-physics simulation and optimization framework. Using three-dimensional anatomic tissue models, we extend the antenna optimization approach for magnetic near-field focusing of (A. Ludwig, C.D. Sarris, G.V. Eleftheriades, IEEE Trans. Antennas Propagat., vol. 62, no. 7, 2014), to determine the current distribution on the probe to best approximate a given temperature profile within the tissue. Subsequently, the optimal current distributions are synthesized by introducing a combination of multiple feed points and reactive loading of the RF probe. Since our design methodology does not rely on introducing sharp edges along the probe (using, for example, a saw-tooth geometry), it results in relatively smooth and therefore, safer probes. Moreover, it offers better control and potentially dynamic reconfigurability of the field and temperature patterns.

Finally, our study illustrates the similarities and differences between synthesizing current sources for sub-wavelength, near-field focusing and synthesizing current sources to achieve a focused temperature profile in biological media. The former optimization is performed with a purely electromagnetic simulation, whereas the latter requires a multi-physics one and directly takes into account the thermal conductivity profile of realistic tissue models.