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Brief Communication

Key issues in bioheat transfer simulations for the application of cryosurgery planning ☆

Yoed Rabin *

Biothermal Technology Laboratory, Department of Mechanical Engineering, Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh, PA 15237, USA

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Abstract

The bioheat transfer simulation is undoubtedly the foundation for developing computerized tools for cryosurgery planning and analysis. While a large variety of techniques for bioheat transfer simulations are available in the literature of the past several decades, it is only their integration with clinical criteria and constraints which can make computerized planning a practical reality. This brief communication outlines (in the opinion of this author) the key issues that must be addressed in the application of bioheat transfer to cryosurgery planning and analysis, while drawing attention to recent and relevant publications in other journals, with reference to the most recent publication on the topic in the *Journal of Cryobiology* [Z. Magalov, A. Shitzer, D. Degani, Isothermal volume contours generated in a freezing gel by embedded cryo-needles with applications to cryo-surgery, Cryobiology 55 (2) (2007) 127–137].

Keywords: Cryosurgery; Simulation; Planning; Bioheat transfer

Dramatic developments in imaging, instrumentation, and computational techniques in recent years have opened new horizons for the application of multi-probe and minimally invasive cryosurgery. Commercial cryoprobes are now available that are as narrow as 1 mm in diameter, and in a wide range of active lengths. These small diameters, and the variability in active length, can potentially improve the surgeon's control over the minimally invasive procedure. In prostate cryosurgery for example, up to 14 small diameter cryoprobes are routinely used, where the most appropriate active length can be selected according to the actual dimensions of the particular organ. One negative aspect of using this large number of cryoprobes is the increased complexity of surgical planning: consider the difficulty of visualizing the 3D shape of the organ (i.e., the target region), while seeking an optimal layout for as many as 14 cryoprobes, in order to best match the transient temperature field with the imaged freezing front and criteria for cryosurgery success.

It is the opinion of this author that the optimal cryoprobe layout must be obtained with the aid of computerized planning tools, relying upon bioheat transfer simulations of the procedure. While numerical techniques for bioheat transfer are well documented in the literature of the past several decades, only a few studies have systematically addressed the critical problem of the best cryoprobe layout for cryosurgery [1,2]; Magalov et al. [4] is the most recent publication concerning this problem—although in a simplistic setup—in the *Journal of Cryobiology*. While the objective to provide results useful for understanding and designing the multi-cryoprobe procedure is commendable, critical evaluation of the Magalov et al. [4] report must incorporate recent and relevant literature [3,5–12] not cited by these authors. (A few of the publications cited here were published only after [4] in archival journal, but are nonetheless relevant to the current discussion; those subjects have been widely presented in conferences in the past few years.) A conceptual difference exists between the studies cited above and the study by Magalov et al.; that difference lies in the lack of a target region (or an organ) to be treated in the latter study. While the comparison of twelve publica-

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* Fax: +1 412 268 2204.
E-mail address: rabin@cmu.edu.

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tions can be space-consuming, the current discussion focuses on four key points [6]: criteria for planning, duration of the procedure, automation, and computer runtime. Without adequate consideration of these key issues, the contribution of bioheat transfer simulations to cryosurgery planning cannot become a practical reality.

Criteria for planning: An inherent disagreement exists between the commonly accepted threshold for cryodestruction (the so-called "lethal temperature") and the monitored parameter during the procedure, which is the freezing front location by means of an imaging technique. In fact, cryoinjury is known to progress within the temperature range bounded by the onset of freezing (at the freezing front) and the lethal temperature. While definitely not the first to disclose the existence of this temperature region, Lung et al. [3] proposed a mathematical criterion to quantify its volumetric magnitude and distribution, terming it a "defect region". The defect region is evaluated with respect to a specific isotherm for planning; the objective being the optimal match of this isotherm to the target region contour. This planning isotherm can be the freezing front temperature, the lethal temperature, or possibly a mid-temperature between the two boundaries, according to the clinician's judgment [3]. The defect region is defined as a region internal to the target region, with temperatures above the planning isotherm (i.e., an internal defect), or an external region to the target region, with temperatures below the planning isotherm (i.e., an external defect). While the existence of a defect region is inherent to the cryoprocedure, computerized planning tools may help to minimize its magnitude and control its distribution. The defect region can be further designed to establish safety margins—either externally or internal to the target region. While Magalov et al. [4] follow the discussion concerning the defect region (with no reference to [3], although they do not use the same term), the lack of target region boundaries in their study does not permit critical evaluation of the defect region distribution, nor does it impose realistic constraints on the duration of the procedure.

Duration of the procedure: The existence of a defect region for a specific number of cryoprobes plays a critical role in predicting the duration of the procedure. For the same example in prostate cryosurgery, and for an organ volume of—say—75 ml (bigger than the size of a typical candidate for such a procedure), the duration of the operation is expected to be between 4 and 18.5 min, using as many as 14, to as few as six cryoprobes, respectively [8], when all the cryoprobes are operated simultaneously in an optimal layout. While the ratio of the volume below the planning isotherm to the volume of the frozen region is quite low at steady state (as also concluded in [4] for different cryoprobes), actual cryoprocedures are ordinarily terminated at the very early stage of the heat transfer process. In fact, several studies suggest that the number of cryoprobes should be increased in order to decrease the internal defect region, which can be concluded from the volume histograms in [9,11,10,12]; the termination of cryosurgery occurs earlier with the increasing number of cryoprobes. Without a target region and matching cryoprobe dimensions, termination of the freezing process remains hypothetical.

Automation: Given the possible irregular shape of the target region [13], and the non-steady temperature field developing in this region, the overwhelming amount of data to be considered requires the implementation of automated tools for planning. Towards this goal, the "force-field" algorithm has been developed [3,5], based on a series of heat transfer simulations and an analogy between the resulting temperature field and forces, which may result in cryoprobes displacement between every two consecutive simulations. A "bubble-packing" algorithm was further developed to identify the most efficient initial condition for the force-field method [9]. Due to its high efficiency, bubble-packing was later demonstrated to be an adequate planning technique, in some cases used alone. As an example, bubble-packing was demonstrated in an intra-operative mode [11], in which planning is modified after the localization of each cryoprobe, due to cryoprobe misplacement as a result of the insertion into the body. Very recently, this algorithm was demonstrated on the full 3D case [10]. In this context, while Magalov et al. [4] selected a series of elementary layouts of up to three cryoprobes and investigated the resulting thermal history, the studies in [3,5,9,11,10] first set the target region and planning criteria, and only then let the computer code seek the best matching layouts for up to 14 cryoprobes. The study in [12] takes automation one step further by planning the so-called "pullback procedure", where a two-cycle freezing protocol is executed, and cryoprobes are incrementally retracted between cycles (see [14] for visualization of that process). The superiority of the implementation of the force-field analogy and the bubble-packing methods over the planning techniques, suggested by Keanini and Rubinsky [2] and Baissalov et al. [1], results from the efficiency in optimization, where prior studies were based on the gradient-descent method, while all cryoprobes may be moved simultaneously in the newer methods, enabling close-to-real-time optimization.

Computer runtime: In order to make computerized planning clinically relevant, it must be carried out within minutes—while the patient is on the operating table—otherwise, the target region may change orientation, deform, or even change size. Magalov et al. [4] used the FEA commercial package Ansys 7.0, which is quite powerful but also very slow (measured in hours for the general 3D case, where systematic planning requires a series of such simulations). Rossi and Rabin [8] have developed a specialized simulation code that can execute the 3D case for a dozen or more cryoprobes in a time scale of one minute. Both the force-field analogy and the bubble-packing techniques use this numerical scheme in the process of planning. This numerical scheme has been validated against experimental results, using proprietary imaging analysis techniques and the defect region concept [7,15]. Such short runtime is critical for any implementation of cryosurgery planning in a clin-

ical setup. While alternative techniques for bioheat transfer simulations are available in the literature, their runtime performance remains to be seen in this context.

In conclusion, the objective of this brief communication is twofold: (i) to point out the critical need for a target when formulating a planning strategy for cryosurgery, or when attempting to provide insight on cryosurgery (without which the bioheat transfer simulation appears to be an academic exercise), and (ii) to outline the key issues that must be addressed in follow up studies, while drawing attention to relevant publications in other journals, as surgical planning represents an interdisciplinary effort. It is recommended that those recent studies be used as benchmarks for future developments.

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References

[1] R. Baissalov, G.A. Sandison, D. Reynolds, K. Muldrew, Phys. Med. Biol. 46 (2001) 1799–1814.
[2] R.G. Keanini, B. Rubinsky, Optimization of multiprobe cryosurgery, ASME Trans. J. Heat Transfer 114 (1992) 796–802.
[3] D.C. Lung, T.F. Stahovich, Y. Rabin, Computerized planning for multiprobe cryosurgery using a force-field analogy, Comput. Methods Biomech. Biomed. Eng. 7 (2) (2004) 101–110.
[4] Z. Magalov, A. Shitzer, D. Degani, Isothermal volume contours generated in a freezing gel by embedded cryo-needles with applications to cryo-surgery, Cryobiology 55 (2) (2007) 127–137.
[5] Y. Rabin, D.C. Lung, T.F. Stahovich, Computerized planning of cryosurgery using cryoprobes and cryoheaters, Technol. Cancer Res. Treat. 3 (3) (2004) 227–243.
[6] Y. Rabin, D. Tanaka, M.R. Rossi, M. Ballinger, K. Shimada, Computerized planning of cryosurgery, CRYO2006—The 43rd Annual Meeting of the Society for Cryobiology, Hamburg, Germany, July 24–27. Cryobiology 53 (3) (2006) 405–406.
[7] M.R. Rossi, Y. Rabin, Experimental verification of numerical simulations of cryosurgery with application to computerized planning, Phys. Med. Biol. 52 (2007) 4553–4567.
[8] M.R. Rossi, D. Tanaka, K. Shimada, Y. Rabin, An efficient numerical technique for bioheat simulations and its application to computerized cryosurgery planning, Comput. Methods Programs. Biomed. 85 (1) (2007) 41–50.
[9] D. Tanaka, K. Shimada, Y. Rabin, Two-phase computerized planning of cryosurgery using bubble-packing and force-field analogy, ASME J. Biomech. Eng. 128 (1) (2006) 49–58.
[10] D. Tanaka, K. Shimada, M.R. Rossi, Y. Rabin, Cryosurgery planning using bubble packing in 3D, Comput. Methods Biomech. Biomed. Eng. 11 (2) (2008) 113–121.
[11] D. Tanaka, M.R. Rossi, K. Shimada, Y. Rabin, Towards intraoperative computerized planning of prostate cryosurgery, Int. J. Med. Robotics Comput. Assist. Surg. 3 (2007) 10–19.
[12] D. Tanaka, K. Shimada, M.R. Rossi, Y. Rabin, Computerized planning of prostate cryosurgery with pullback procedure, Comput. Aided Surg. 13 (1) (2008) 1–13.
[13] http://www.me.cmu. edu/faculty1/rabin/ProstateModelReconstructionF.htm.
[14] http://www.me.cmu.edu/faculty1/rabin/PullbackModelDF.htm.
[15] http://www.me.cmu.edu/faculty1/rabin/ExperimentalVerification.htm.