Design of HIFU Treatment Plans using an Evolutionary Strategy

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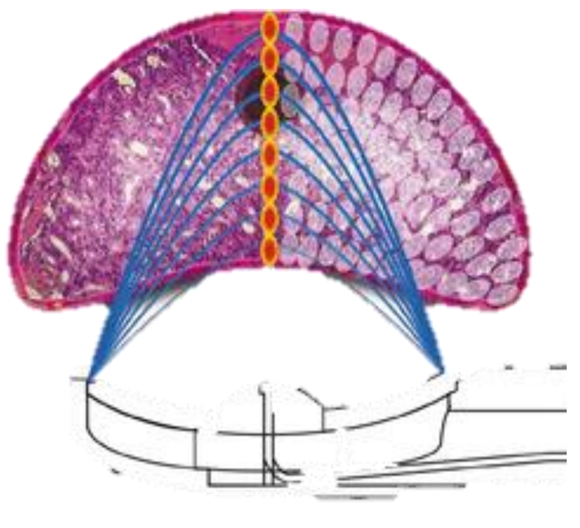
1 Introduction

High Intensity Focused Ultrasound (HIFU) is an emerging technique for non-invasive cancer treatment where malignant tissue is destroyed by thermal ablation.

Since one ablation only allows a small region of tissue to be destroyed, a series of ablations has to be conducted to treat larger volumes.



To maximize the treatment outcome and prevent injuries, complex preoperative treatment planning is carried out. The treatment planning problem is defined as a search for the optimum position and sonication times for the specified number of ablations to destroy the desired target volume while sparing the organs at risk.

2 Solution Encoding

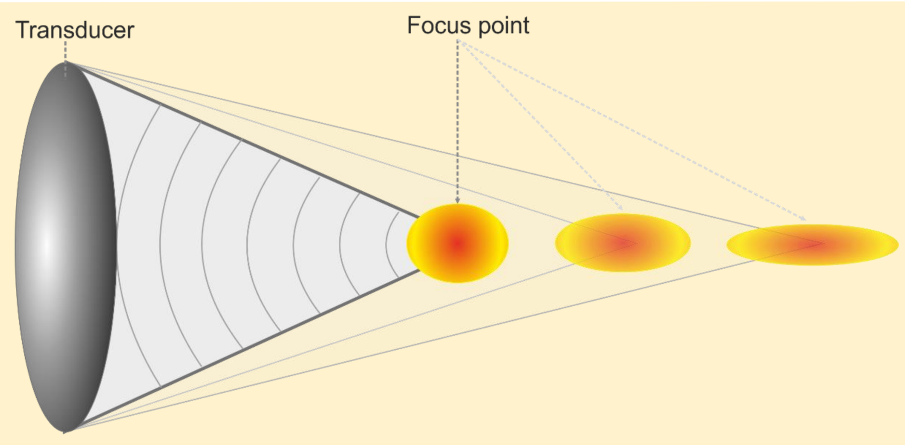
An optimization algorithm based on the Matlab implementation of the Covariance Matrix Adaptation (CMA) Evolutionary Strategy (ES) was used. This evolutionary strategy uses a map of patient specific material properties and a realistic thermal model.

One sonication is represented by a 4-tuple S_i composed of two spatial coordinates of the focus beam (only 2D problems are considered), and the sonication and cooling intervals:

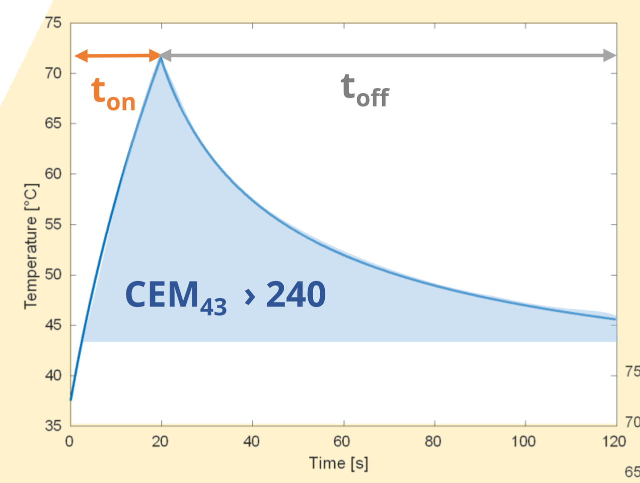
$$I = (S_1, S_2, \ldots, S_n), \quad where\ S_i = (x_i, y_i, t_{\mathrm{on},i}, t_{\mathrm{off},i})$$

3 Fitness Function

Calculation of the Heat Deposition

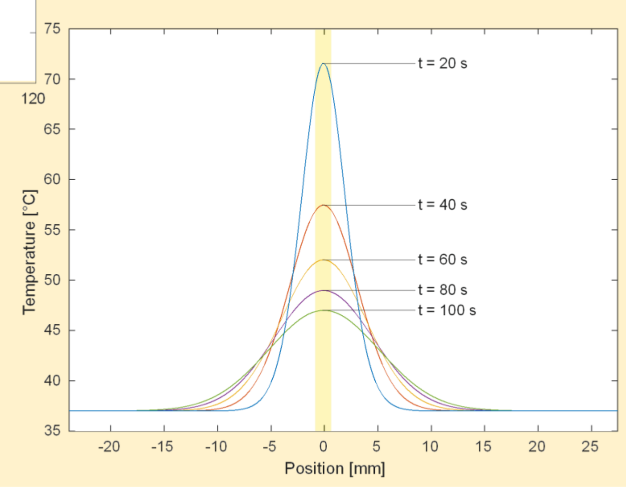


Thermal Model Execution



The temperature course during the sonication is calculated at each point.

A temperature distribution evolution in time along the main focus axis is shown in the picture on the right.



Evaluation of the Treated Area

Dimensions · Desired area · Prohibited area · Non-treated area · Treated area

$$f = \int_0^X \int_0^Y ((D * \bar{C}) + (P * C))\,dxdy$$

$$C = \begin{cases} 0 \text{ for } CEM_{43} \leq 240 \\ 1 \text{ for } CEM_{43} > 240 \end{cases}$$

$$\mathrm{D} \in \mathbb{R}^+, \mathrm{P} \in \mathbb{R}^+$$

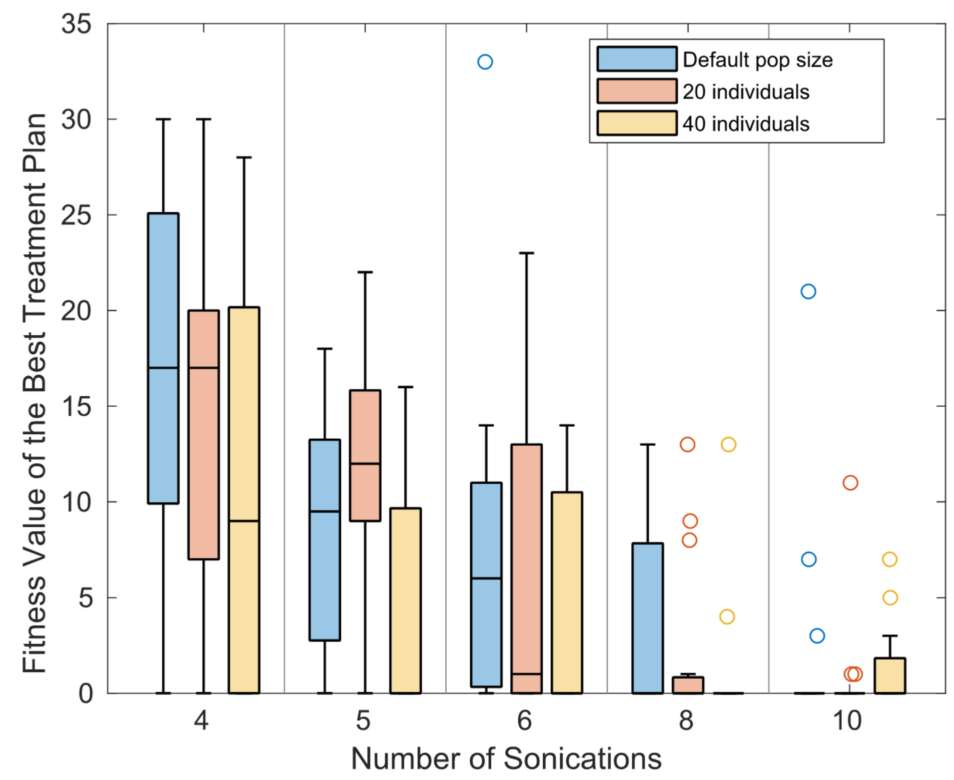
4 Cumulative Equivalent Minutes Metric (CEM)

$$CEM_{43} = \int_0^{t_{\mathrm{on}}+t_{\mathrm{off}}} R^{(43-T)}dt, where$$

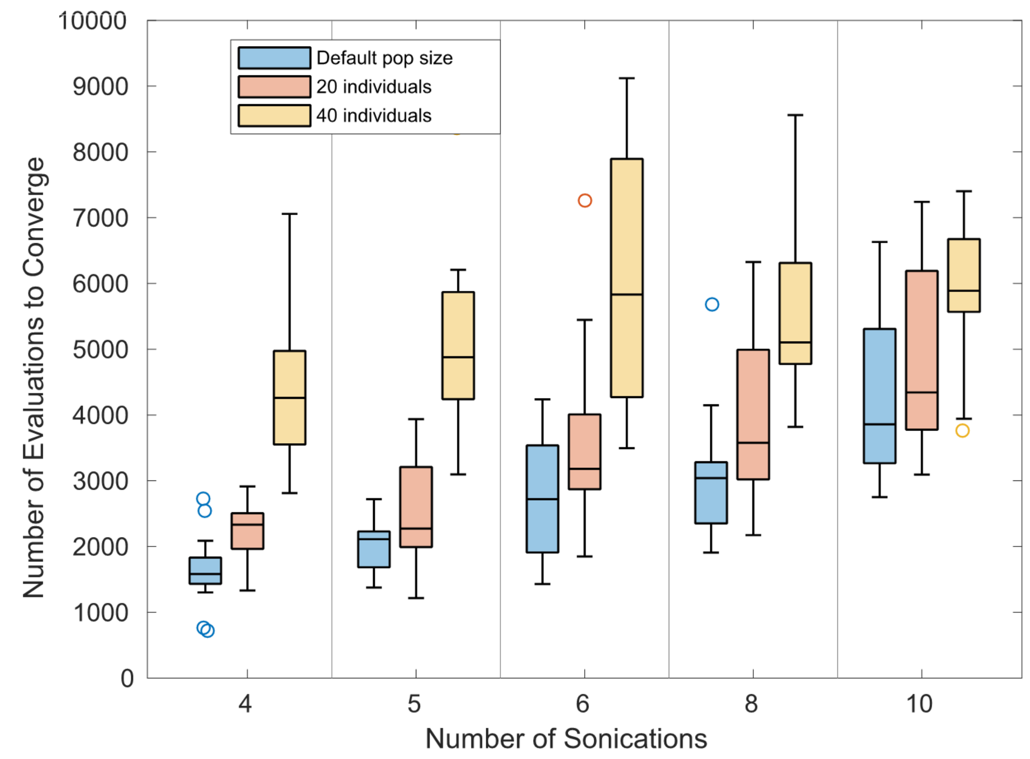
$$R = \begin{cases} 0 \text{ for } \mathrm{T} \leq 39°\mathrm{C} \\ 0.25 \text{ for } 39°\mathrm{C} < \mathrm{T} \leq 43°\mathrm{C} \\ 0.5 \text{ for } \mathrm{T} > 43°\mathrm{C} \end{cases}$$

This metric presents the equivalent time which would produce the same biological effects at a temperature of 43°C. Thermal doses of 240 minutes at 43°C irreversibly damage and coagulate critical cellular protein and tissue structural components.

5 Experimental Results



The population size has only a minor influence on the treatment plan quality, but has a significant impact on the number of evaluations carried out. Contrary, the number of sonications has a very positive impact on the treatment plan quality for only a modest increase in the number of evaluations. However, the evaluations become more complex.

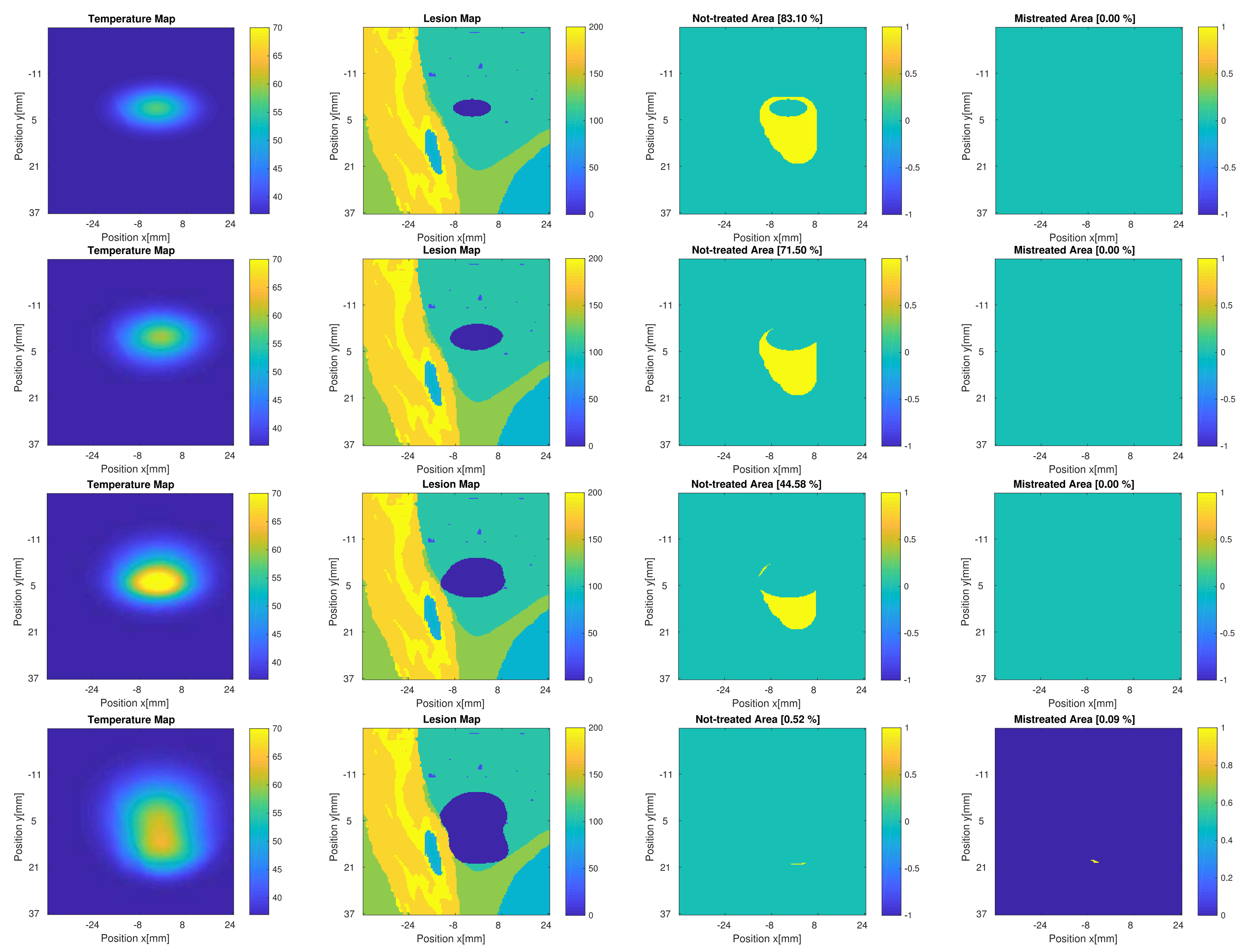


The best trade-off between the treatment plan quality and the number of sonications seems to be 8 sonications and the population size of 20 or 40 individuals.

The median of the percentage of non-treated/mistreated area from 15 independent runs as a function of the population size λ and the number of sonications is shown in the table. The typical mistreated and non-treated area doesn't exceed 0.1%.

	Number of Sonications				
λ	4	5	6	8	10
default	0.03/0.10	0.02/0.06	0.02/0.04	0.00/0.00	0.00/0.00
20	0.00/0.11	0.00/0.09	0.00/0.01	0.00/0.00	0.00/0.00
40	0.00/0.09	0.00/0.00	0.00/0.00	0.00/0.00	0.00/0.00

6 Visualization of a Treatment Plan



7 Conclusions

The proposed strategy allows high-quality treatment plans to be designed with the average area of mistreated and non-treated tissue not exceeding 0.1%.

This approach now takes between 36 to 48 hours to create a good treatment plan in 2D. This issue will be addressed as the next step in our research, which consists of the reimplementation of the whole algorithm in high performance languages with the aim to reduce the computational time by a factor of 5, at least.

k-Wave
A MATLAB toolbox for the time-domain simulation of acoustic wave fields

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