Three-dimensional reconstruction of subsurface absorbing structures in human skin from photothermal radiometric records

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Pulsed photothermal radiometry (PPTR) involves analysis of transient changes in mid-infrared (IR) emission from a sample surface after irradiation with a short light pulse. From a radiometric record obtained with a fast IR camera, light-induced temperature field inside the sample can be reconstructed in three dimensions (3D) by solving the inverse problem of heat diffusion and blackbody emission [1]. This could enable visualization of selectively absorbing structures in strongly scattering biological tissues and organs, similarly to photoacoustic microscopy and tomography [1,2]. However, development of a practical, accurate and robust methodology has remained elusive, primarily due to the scale and severe ill-posedness of the iterative image reconstruction process, emphasized by the low signal-to-noise ratios in the available radiometric records.

We present a parametric optimization study of the image reconstruction process using simulated radiometric records based on realistic experimental parameters, such as the mid-IR absorption and thermal properties of human skin (including the convective boundary condition) as well as the spatial resolution, acquisition rates, and noise characteristics of an actual mid-IR camera (FLIR SC7500) equipped with a microscope objective (magnification $M = 1$). The image reconstruction code written in Python performs the multidimensional optimization of the initial, laser-induced temperature field in three dimensions by running non-negatively constrained "ν-method" minimization algorithm [3].

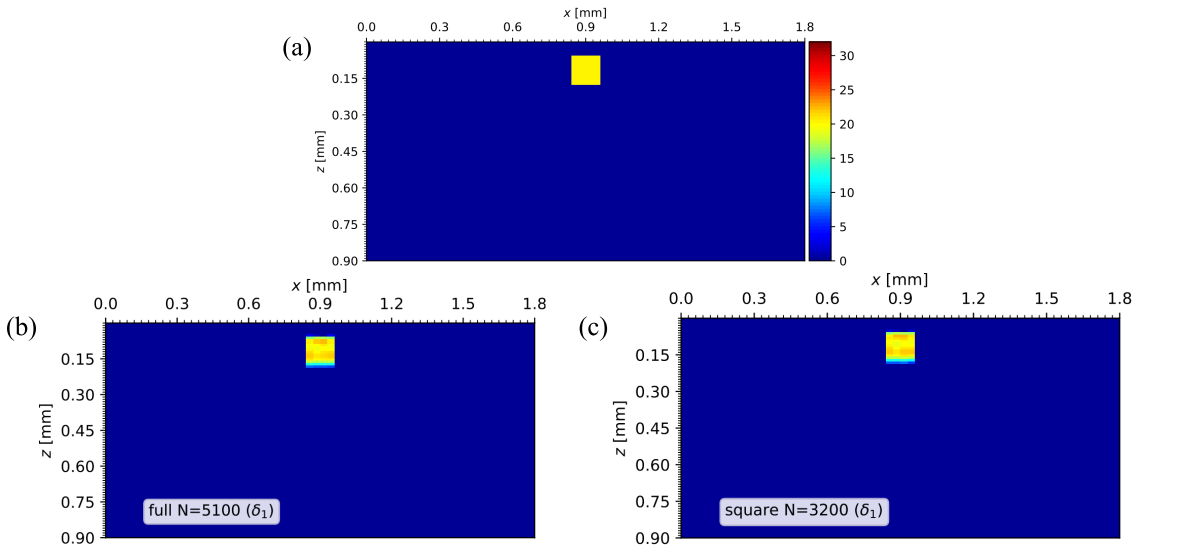

Fig. 1. (a) Postulated initial temperature field, emulating a sub-surface block with a square cross-section (0.12 x 0.12 mm^2) heated to 20 K above the surrounding medium. (b) The cross-sectional image reconstructed from the complete simulated radiometric record, consisting of 1250 IR images at 1000 fps (including noise), and (c) by applying progressive binning of the radiometric frames for significant reduction of the computational time.

The example presented in Fig. 1 involves an extended sub-surface block ("blood vessel") with a square cross-section (0.12 x 0.12 mm^2) and initial temperature 20 K above the surrounding medium. At the spatial discretization of 30 μm in the lateral and 10 μm in the axial direction, the reconstruction of vertical cross section through its center involves optimization of 5400 independent temperature values.

As demonstrated in Fig. 1b, this was accomplished very successfully in 5100 steps of the iterative reconstruction process when using the entire radiometric record, consisting of 1250 images "acquired" at 1000 frames per second (t_{max} = 1.25 s). The obtained image features our object in the correct location and with rather sharp edges, and no artifacts anywhere else in the reconstructed vertical plane.

Moreover, our analyses demonstrate that preconditioning of the input dataset by progressive binning of subsequent radiometric frames can significantly reduce the computational cost of the reconstruction process without adversely affecting the outcome. In the presented example, a nearly identical result was obtained by applying the so-called square temporal binning [4], which reduced the input radiometric record to only 250 images (Fig. 1c). In addition to speeding up the reconstruction process by a factor close to 5, this produced an image of the same quality in only 3200 iteration steps, thus offering an additional 37% reduction of the computation time.

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References

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