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Assessing the internal composition of the intervertebral disc with photoacoustic imaging: a numerical study

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ABSTRACT

Disc degeneration diseases appear due to the natural process of dehydration of the intervertebral disc (IVD). Treatment options help to relieve pain but still impact the spine integrity in the form of a decrease in mobility and acceleration of the degenerative process of the neighbouring discs. Early diagnosis of degeneration is therefore interesting to limit the progression of the diseases and avoid pain. Effective diagnosis methods exist such as magnetic resonance imaging or computerized tomography but they lack flexibility and time effectiveness. We propose the use of photoacoustic imaging as an alternative quantitative method to assess the state of the IVD. We present the results of a preliminary study where numerical reconstructions of the principal chromophores composition (water/collagen) of the IVD were obtained using a gradient descent scheme.

Keywords: Photoacoustic, Interverbral disc, Inverse problem, Quantitative Photoacoustic Imaging

1. INTRODUCTION

Intervertebral disc (IVD) are fibrocartilaginous organs that ensure the cohesion and mobility of the spine. They are highly hydrated tissue,¹ however this water content decreases with time and can provoke diverse problems² such as low back pain. This dehydration process, called disc degeneration, is a natural process which continues throughout life. This process can accelerate due to bad behaviours and other various factors leading to pathological conditions. The actual common treatment methods for the degenerated disc consist of disc excision or spinal fusion, which lower the spine mobility and accelerate the degeneration of the neighbouring discs.³ However, the use of hydrogels is currently being investigated as an innovative treatment option.

As the current treatment methods are detrimental to the spine integrity, early diagnosis of the first stages of degeneration is of great interest to prevent future pathological complications. Diagnosis of the disc is currently commonly assessed through the use of magnetic resonance imaging (MRI),⁴ which achieves accurate estimation of the main components (water and collagen mainly) concentration in the disc. Computerized tomography (CT) is used as well, and provides complementary information. We propose a quicker and more flexible approach using photoacoustic (PA) imaging to probe the IVD.⁵ From PA measurements, it is possible to access quantitative information on the chromophores concentration in the IVD and, hence, assess its state. Here the study is focused on the resolution of the optical inverse problem. Synthetic PA measurements are obtained using a numerical phantom of an IVD. The accomplished numerical study shows the feasibility of the approach for the 3D recovery of the quantity of interest.

2. MATERIALS AND METHODS

The IVD morphology was obtained from an MRI of a porcine IVD⁶ (see figure 1). The 3D matrix representing the morphology consists of a grid of $77 \times 19 \times 104$ voxels. The reconstructions were performed on a coarser grid of $39 \times 10 \times 52$ voxels to avoid the inverse crime. The source configuration is presented in the figure 1 as well. Optical properties (absorption μ_a , scattering μ_s and anisotropy g coefficients) as well as the spatial distribution of the main components of the IVD (water and collagen) gathered from the literature allowed us to define the

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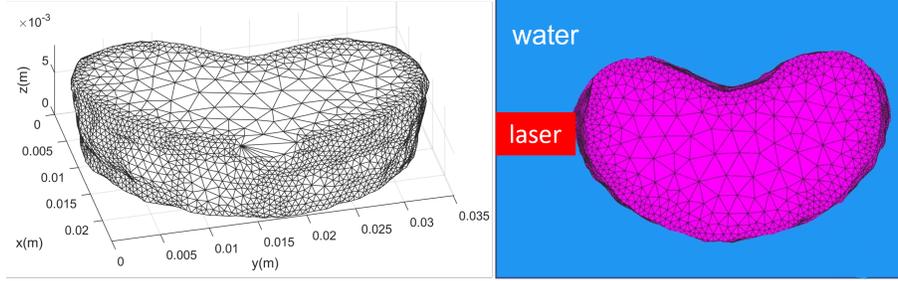


Figure 1. IVD morphology (left) and source configuration (right) used in the reconstructions

spatially varying optical parameters of the disc: as the optical properties depend on the composition of the disc, the absorption and scattering coefficient were defined from the chromophores' proportions at position r and at wavelength λ as:

$$\mu_a(\lambda, r) = \sum_{k=1}^N \alpha_k(\lambda) p_k(r); \quad \mu_s(\lambda, r) = \sum_{k=1}^N \sigma_k(\lambda) p_k(r), \quad (1)$$

with N being the total number of chromophores, α_k and σ_k the absorption and scattering coefficients of the chromophore k respectively and $p_k(r)$ the proportion of the chromophore k at the position r (with $\sum_{k=1}^N p_k(r) = 1$). Using the numerical phantom, synthetic measurements of the initial pressure $p_0(\lambda, r)$ were simulated. The initial pressure is defined as:

$$p_0(\lambda, r) = \Gamma(r) \mu_a(\lambda, r) \phi(\mu_a(\lambda, r), \mu_s(\lambda, r), g(\lambda, r)), \quad (2)$$

with Γ the Grüneisen parameter and ϕ the fluence. MCmatlab⁷ was used to calculate ϕ . The synthetic measurement were degraded by adding Gaussian noise to test the robustness of the algorithm. The reconstruction has been restricted to a limited part of the IVD. This restricted area was defined to avoid low signal to noise ratio area. The resolution of the inverse problem was performed through the minimisation of an error function ϵ defined as:

$$\epsilon = \int_{\Omega} (p_{meas} - p_0)^2, \quad (3)$$

where Ω is the volume of interest, and p_{meas} the synthetic measurement. A gradient descent scheme was used and the necessary gradients were calculated. The Barzilai-Borwein step size⁸ was used to significantly improve the speed of the reconstruction. The algorithms were stopped when the error function variations were below a defined threshold.

3. RESULTS

We present here an example of reconstruction in figure 2. In this example, the proportion of collagen in the disc was recovered. The error function evolution and a 1D profile reconstruction of the collagen proportion are presented in figure 3.

4. CONCLUSION

The obtained results show a promising future for photoacoustic as a means of probing the IVD.

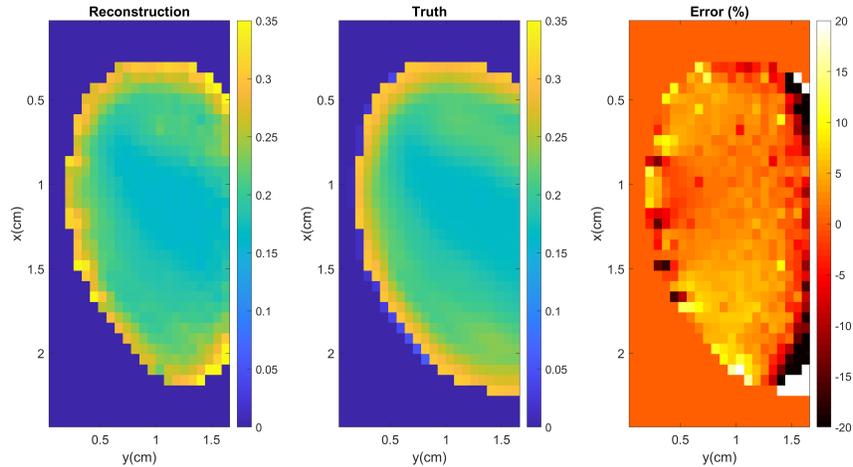


Figure 2. Reconstruction results (left) *vs.* ground truth (center). Error is indicated in % on the right.

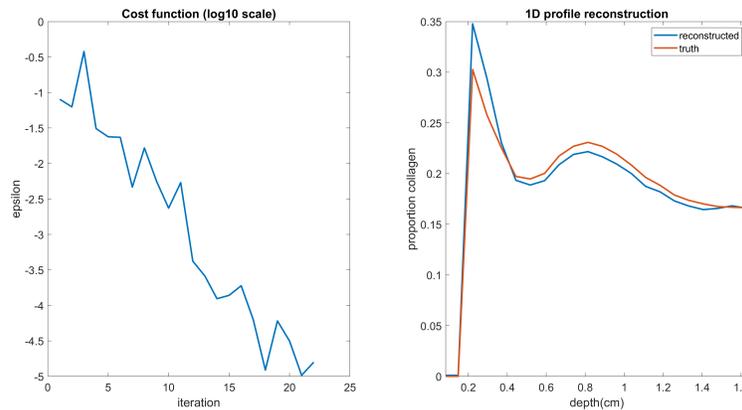


Figure 3. Error function ϵ evolution in log scale (left) and 1D profile reconstruction *vs.* ground truth.

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