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Assessment of intervertebral disks viability with quantitative photoacoustic tomography

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Abstract: Intervertebral disks face age-related changes in their composition. We propose photoacoustic imaging to measure the relative water/collagen composition in depth. The feasibility is illustrated on a numerical phantom of a disk. © 2022 The Author(s)

1. Introduction

The intervertebral disk (IVD) is a fibrocartilaginous organ present between the vertebrae of the spine. Together, they ensure the mobility of the back and act as shock absorbers. This organ is known to possess a high proportion of water. However, as time passes, its composition changes and it loses water [1, 2]. These alterations lead to degenerative disk diseases (e.g. herniated disk or scoliosis) and pain [3]. The composition of the disk is therefore an important indicator of the health of the IVD.

Diagnosis of the disk is commonly performed using Magnetic Resonance Imaging (MRI) or Computerised Tomography (CT) [4]. We evaluate here the feasibility of using PhotoAcoustic (PA) imaging to probe the IVD, a more portable technique. Indeed, from spectroscopic PA measurements, one can recover the chromophores (water/collagen/proteoglycans) distribution and, therefore, assess the viability of the probed disk.

To show this possibility, a numerical study has been conducted on a digital IVD, obtained from MRI measurements. A gradient-based resolution of the optical inverse problem has been implemented, based on the resolution of the forward model with the Radiative Transfer Equation (RTE) by Monte Carlo simulations. A numerical study conducted under various configurations and situations shows the feasibility of the approach on the reconstruction in 3D of the absorption coefficient μ_a , at given wavelengths, from which, if spectroscopic measurements are performed, the water/collagen composition of the IVD can be obtained.

2. Methods

The morphology of an IVD of a pig was recovered from MRI [5] and is presented on Fig. 1. The IVD consists of two distinct parts: a central part called the Nucleus Pulposus (NP) circled by concentric lamellae forming the Annulus Fibrosus.

In the present model, the NP was simulated by a cylinder at the center of the disk. The spatial distribution as well as the optical properties (absorption and scattering coefficients μ_a and μ_s , and anisotropy parameter g) of the main components (water/collagen) were gathered from the literature, allowing us to model the spatially-varying optical properties inside the IVD. For simplicity, the Grüneisen coefficient Γ of the disk is supposed to be 1, but could also be more precisely modeled. Synthetic measurements of the initial pressure distribution, $P_o = \Gamma\mu_a\phi(\mu_a, \mu_s, g)$, ϕ being the fluence, can be obtained under various configurations. MCmatlab [6] was used to compute ϕ .

The optical inverse problem was solved using a gradient descent scheme by the minimisation of an error functional \mathcal{E} . The gradient of this functional with respect to the parameter of interest $\frac{\partial \mathcal{E}}{\partial \mu_a}$ was calculated through the resolution of a forward and an adjoint problems formulated respectively for the radiance L and the adjoint radiance L^* [7]. These quantities can be calculated by solving the RTE and its adjoint counterpart using Monte Carlo (MC) methods. MCmatlab [6] is modified for the computation of both forward and adjoint radiances. To handle spatial and angular diskretizations for the evaluation of the radiance, a decomposition into spherical harmonics was adopted [8].

3. Results

An example of results is shown in Fig. 2. It presents the reconstruction of μ_a after 50 iterations of the gradient descent scheme. The laser configuration is presented as well. Laser radius is 1.5mm. MC calculations for both the forward and adjoint radiances were implemented with approximately 10^7 photons at each iteration.

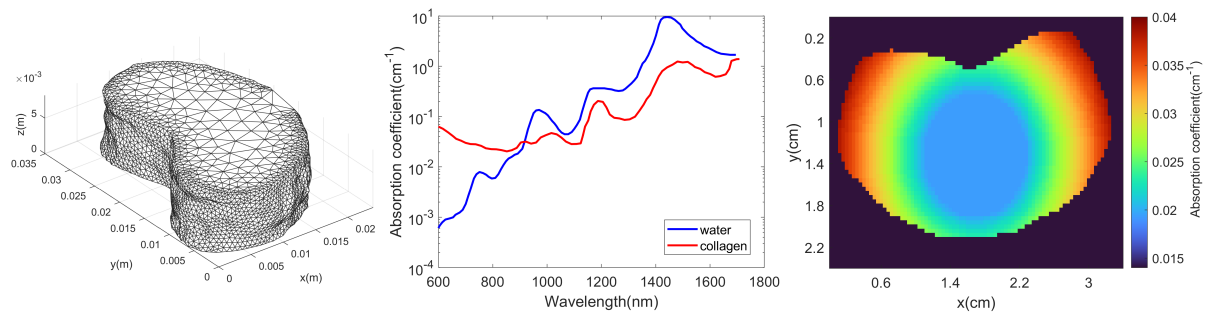


Fig. 1. Left: Morphology of the IVD obtained by MRI [5]. Center: Optical absorption of collagen and water [9]. Right: 2D visualization of the spatially-varying absorption coefficient inside the IVD structure.

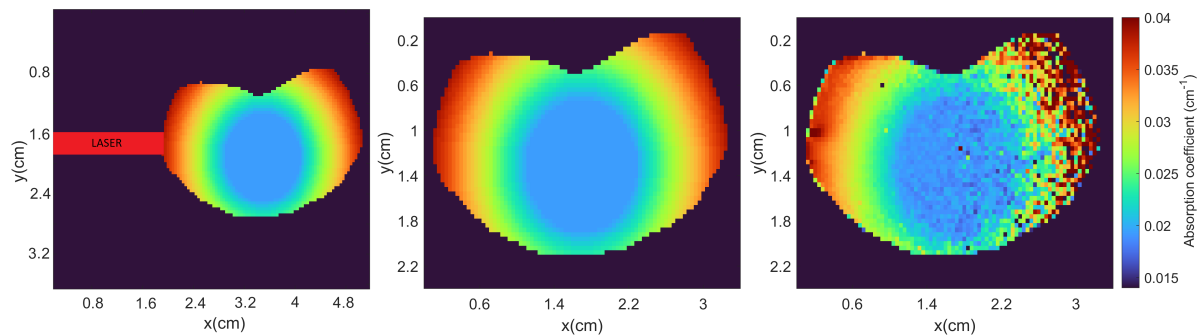


Fig. 2. Reconstructed absorption coefficient (right) compared to the actual absorption coefficient inside the disk (center). Illumination configuration is presented on the left.

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