Imaging of Rheumatoid Arthritis in Finger Joints by Sagittal Optical Tomography

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Summary

In early stages of rheumatoid arthritis some changes in joints arise due to an inflammatory process. In the case of transillumination with near infrared light these changes affect the radiation transport in joints. We performed first numerical simulations for a basic approach of a sagittal optical tomographic imaging method that led to promising results. For this purpose, the optical properties of the different tissue types in joints were measured and NMR images were used for geometrical model development and visualisation of rheumatoid arthritis.

Key words

Rheumatoid arthritis, finger joint, optical tomography

Introduction

Chronic diseases like inflammmable rheumatic diseases are of special importance because patients require an expensive long-term therapy and generally have to withdraw from working life soon. The most frequent inflammmable rheumatic disease is rheumatoid arthritis (RA), an autoimmune disease. RA most frequently affects the finger joints. Steinbrocker (2) has divided the process of RA in joints in four stages (Fig. 1). Conventional diagnosis is principally made by clinical and laboratory examination of joints assisted by radiographs. For a specific therapy, a secure finding is indispensable. Unfortunately, radiographs suffer from poor contrast for soft tissue so that one cannot identify changes until cartilage and bone destruction is obvious (stage 3). Ultrasound and NMR examination enables recognition of changes of soft tissue (3) but the diagnostic benefit of ultrasound at finger joints is disputed. The safest method for recognition of early inflammatory arthritis is nuclear magnetic resonance imaging (NMR) in combination with contrast agents. But high costs argue against this method especially for small joints. The structural changes in early
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At first, a numerical model of the finger joint is required considering both the anatomical and optical properties of the joint (Fig. 2). Light transport through tissue is affected by absorption of water and chromophores, and scattering at structures like membranes, cell cores, or large molecules like lipids (1). The optical properties of tissue are therefore characterised by the absorption coefficient $\mu_a$, the scattering coefficient $\mu_s$, and the anisotropy factor $g$ which considers the probability of scattering direction. In previous investigations (6) we determined optical properties like scattering and absorption in proximal interphalangeal (PIP) finger joints (6). In earlier studies we used a simple transillumination technique with a red diode laser on the upper side of a finger joint and a CCD camera to capture the diffuse transmitted light on the underside (7). A complex analysis of the data obtained with huge computational effort provides information about the inflammatory status but no real image of the joint. An image representing the optical properties in the finger joint requires a tomographic method. A simple approach is to perform a sagittal scan in the central plane along the finger axis with illumination on one side and radiation detection on the opposite side. Klose et al. (5) developed mathematical methods that enable forward calculation and reconstruction of optical parameter distribution. Simulation of sagittal diffuse optical tomography of a PIP finger joint was performed in healthy and early inflammatory stage and results were compared to NMR images. Experimental examination with a sagittal optical tomograph is in progress.

Materials and Methods

How does simulation of sagittal optical tomography work?
Fig. 3. Mathematical scheme for the reconstruction of optical parameters (5). The goal is to minimize the objective function (sum over the differences between measured and predicted detector readings for every source detector combination). The results are images representing the real distribution of optical parameters in the transilluminated plane.

Fig. 4. NMR images of two PIP joints of a 60 years old patient, T1 weighted. 1 – no inflammation, no contrast agent; 2 – inflammatory RA state with contrast agent gadolinium.

Predictive of Detector reading
Forward Calculation
(equation of radiative transfer, discrete-ordinate, finite-difference method)

Objective Function
\[ \phi(\mu_k) \]

Gradient Calculation
(adjoint differentiation method)

\[ \gamma = \Delta \phi(\mu_k) / \Delta \mu_k \]

Search Direction

\[ t^l = M_{k-1} \]

Update

\[ \mu_{k+1} = \mu_k + \alpha_t \]

Forward Calculation

\[ P_{\mu_{k+1}} (\text{Source, Detector}) \]

\[ \Delta \text{Objective Function} \]

\[ \phi(\mu_{k+1}) - \phi(\mu_k) \leq \epsilon \]

In another step, the light transport through the finger is calculated by applying the theory of radiation transfer (4). For each of 10 source positions along the finger the detector response at 40 positions is calculated. This leads to \(10 \times 40 = 400\) data. Due to the multiple scattering of light in tissue the transmission of light is deeply diffuse. Therefore nearly every position in the rectangle between sources and detectors is transilluminated. The ‘measured’ data are finally used as input for the reconstruction algorithm (Fig. 3). The results are images representing the distribution of optical parameters in the transilluminated plane.

**Results**

For an exact documentation we made sagittal NMR images of two PIP joints of a 60 years old patient (Fig. 4) with comparison between non inflamed joint (Fig. 4.1) and inflammatory RA state (Fig. 4.2). The contrast agent in the inflamed joint verifies a physiological RA stage of 2 (Fig. 1). Beside the overall thickening of the finger the swollen capsule is clearly visible due to increased blood flow in the inflamed synovialis and the diffusion gradient into the affected partial volume. As we discovered during optical tissue parameter measurements (6), an inflammatory stage of 1 and 2 implies an increase in light scattering in the joint region. This is physiologically correlated to changes of the synovialis and an increase of the concentration of lipids and cells.

ties of the main anatomic components in healthy and rheumatoid finger joints. The numerical model contains a simplified distribution of the optical properties corresponding to the main components of a finger joint.
the number of sources and detectors in this region. Therefore these outer positions are less transilluminated. This causes a lack of information for exact reconstruction. The high scattering spots beneath the source positions and the increase in scattering in the direction of the outer detector positions are artefacts too. The results for the distribution of absorbers are not shown because the changes are very small.

**Outlook**

First simulations of sagittal optical tomography of RA in finger joints point out that this imaging method will be sensitive to changes in the scattering behaviour in the joint. This will make an alteration of the expanded capsule better to visualise than changes in the narrow joint gap. In the near future we will perform clinical measurements with an experimental setup to find out if sagittal images of optical properties can safely detect the state of inflammation. For this purpose, we will embed the finger and the optical scanning head in a scattering fluid because this will lead to optimal conditions for light coupling in the finger and to optimal reconstruction results. In addition, new specific fluorescent marker offer the possibility to combine optical tomography with fluorescent imaging techniques. So, by combination of scattering, higher absorption and fluorescence inflamed areas will be characterised at improved resolution and accuracy. Therefore we expect optical tomography to become a useful tool to assist rheumatologists in early diagnosis of RA.

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**Darstellung von rheumatoider Arthritis in Fingergelenken mittels Sagittaler Optischer Tomographie**

Im Frühstadium der rheumatoiden Arthritis kommt es in Gelenken durch einen entzündlichen Prozess zu Veränderungen, die bei einer Durchleuchtung mit nah infrarotem Licht den Strahlungs-transport beeinflussen. Wir haben erste Simulationsrechnungen für einen einfachen Ansatz einer sagitallen, optisch tomographischen Bildgebung von PIP-Gelenken durchgeführt, die zu viel-

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**Fig. 5.** Reconstructed scattering coefficient $\mu_s$ in the transilluminated plane of the model (Fig. 2). 1 – healthy stage; 2 – synovialis and synovial fluid with optical properties of inflamed stage; 3 – only synovial fluid inflamed, dark areas indicate high scattering.
versprechenden Ergebnissen führten. Dafür wurden die optischen Eigenschaften der unterschiedlichen Gewebetypen in Gelenken gemessen und MRT-Bilder für die geometrische Modellbildung und die Visualisierung der rheumatoiden Arthritis genutzt.

**Schlüsselwörter**
Rheumatoide Arthritis, Fingergelenk, Optische Tomographie

**References**


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