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Three-dimensional diffuse optical imaging of hand joints: System description and phantom studies

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Abstract

In this paper we describe a three-dimensional (3D) continuous wave (CW) diffuse optical tomography (DOT) system and present 3D volumetric reconstruction studies using this DOT system with simple phantom models that simulate hand joints. The CCD-based DOT system consists of 64×64 source/detector fiber optic channels, which are arranged in four layers, forming a cylindrical fiber optic/tissue interface. Phantom experiments are used to evaluate system performance with respective to axial spatial resolution, optical contrast and target position for detection of osteoarthritis where cartilage is the primary target region of interest. These phantom studies suggest that we are able to quantitatively resolve a 2 mm thick "cartilage" and qualitatively resolve a 1 mm thick "cartilage" using our 3D reconstruction approach. Our results also show that optical contrast of 3:1–7:1 between the "disease cartilage" and normal cartilage can be quantitatively recovered. Finally, the target position along axial direction on image reconstruction is studied. All the images are obtained using our 3D finite-element-based reconstruction algorithm.

Keywords: Diffuse optical tomography; Three-dimensional imaging; Joints

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1. Introduction

Diseases related to joints such as osteoarthritis and rheumatoid arthritis are a major cause of morbidity in the population over 50. Conventional imaging methods such as X-ray radiography and ultrasonography are not appropriate for early detection of such diseases, because they provide only tissue structural information. Near-infrared (NIR) diffuse optical tomography (DOT) can provide both structure and functional images of thick tissues [1–7]. Spatial maps of tissue optical properties can be recovered by model-based reconstruction methods using measured diffusive data. Pilot studies have shown that DOT has the potential to become a powerful, yet cost effective imaging modality for early detection of joint diseases due to significant difference/contrast in optical properties between normal and diseased joint tissues [8–10].

In our early work [10], we have indicated that 3D image reconstruction approach is needed for joint imaging due to the strong 3D scattering of light in the joints. We have demonstrated that 3D images of a healthy finger joint can be reconstructed using data collected from a single photomultiplier tube (PMT)-based detection system. Clearly the single PMT-based detection system is too slow for 3D data collection and essentially not suitable for clinical studies. Thus it is desirable to develop a parallel detection-based system for fast 3D data collection. In addition, it is necessary to perform controlled phantom studies so that system performance can be evaluated and future in vivo results can be analyzed/interpreted properly.

When developing a parallel detection system, choice of sensitive and efficient detectors are important. While several types of photodetectors are available for weak signal detection, we are interested in using charge-coupled device (CCD) for 3D imaging of joints. CCD camera can achieve parallel signal collection without any increase in system complexity. In fact, CCD camera has been applied for DOT imaging [11–13]. While these applications of CCD in DOT are focused on imaging of the breast and brain, we are interested in a CCD-based continuous wave (CW) DOT system specifically for joint imaging. The CCD-based system described here consists of 64×64 source/detector fiber optic channels. All the optic fibers are placed along the surface of a 30 mm diameter cylinder for finger joint measurements. The parallel detection allows us to collect a full set of 3D tomographic data (64×64) within 7 min.

A series of phantom experiments are designed and conducted to study 3D joint imaging using the CCD-based system developed. Since we are particularly interested in osteoarthritis imaging, we have used a simple phantom model that allows us to evaluate the capability of the system for imaging of "cartilage", the most important joint component involved in osteoarthritis. It is critical to examine whether or not DOT is able to resolve this thin joint tissue for detection of osteoarthritis. We note that an adult articular cartilage has a typical thickness from 2 to 4 mm [14]. This means that the bone-to-bone joint region should at least be of the same order. To address resolution issue specifically, in this paper we have used phantom experiments to demonstrate that resolution of 2 mm can be obtained using our 3D reconstruction approach given a typical size of the human finger. In the phantom results presented,