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Development of a Finger Joint Phantom for Evaluation of Frequency Domain Measurement Systems

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Abstract— **For development and test of new optical imaging devices, phantoms are widely used to emulate the tissue to be imaged. Phantom design gets more difficult the more complex the tissue is structured. We report on developing and testing a solid, stable finger joint phantom to simulate transillumination of finger joints in frequency-domain imaging systems. The phantom consists of the bone, capsule, skin, the capsule volume, and the joint gap. Silicone was used to build the solid parts and a glycerol-water solution for the fluid in the capsule volume and joint gap. The system to test the phantom is an optical frequency-domain scanning set-up. Different stages of joint inflammation as they occur in rheumatoid arthritis (RA) were emulated by assembling the phantom with capsule and fluid having different optical properties. Reliability of the phantom measurement was investigated by repeated assembling. The results show clear discrimination between different stages of joints within the signal deviation due to reassembling of the phantom.**

I. Introduction

RHEUMATOID arthritis (RA) is a widespread disease and a common reason for becoming incapable of working. RA mostly affects joints, especially finger joints. Recurring inflammation leads to progressive destruction of cartilage and bone, which ultimately leads immobility of the joints and severed impairment of the hand. X-ray radiography is the standard imaging procedure to detect changes in joints. Unfortunately x-ray radiography shows only changes to the bone but not the early inflammation process. However, an early diagnosis is crucial for stopping the progression of disease by choosing the optimal treatment regimen. Compared to X-ray imaging, magnetic resonance imaging (MRI) is much more sensitive to soft tissue structures but requires the use of a contrast agent and is comparatively expensive. Ultrasound is particularly useful for the assessment of soft tissue but the documentation is time-consuming and accurate interpretation requires considerable observer training.

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During the inflammation process of a joint, significant changes occur in absorption and scattering properties in the visible and near infrared electromagnetic spectrum [1,2]. Making use of these changes, we introduced a simple diaphanoscopic transillumination method and performed first clinical studies [3]. By analysis of the scattered light distribution it was possible to demonstrate that the inflammation stage can be evaluated in follow-up examinations. In further studies, maps of the optical properties in a joint were reconstructed by using a steady-state optical tomographic imaging system and a model-based iterative reconstruction scheme using the theory of radiation transport [4,5]. We found that it is possible to correctly evaluate the inflammatory stage in primary diagnostics. However, optical methods still suffer from relatively poor spatial resolution and crosstalk between absorption and scattering maps because the mathematical system is under-determined. These problems could be ameliorated by employing frequency domain (FD) methods instead of a steady-state system. In FD methods the light intensity is modulated in time by radio frequencies (RF) (~100 to 1000 MHz). The light passes through the tissue as a so-called photon density wave (PDW) and shows frequency-dependent amplitude damping and phase delay. Using FD data, reconstruction of tomographic images should show better spatial resolution and the differentiation between absorption and scattering effects should be enhanced. Therefore our ongoing research focuses on FD optical tomography of finger joints.

In FD tomographic imaging there are several parameters that can be varied to find the optimal working point e.g. source modulation frequency, modulation depth, and detector amplification. Whereas early studies in biomedical imaging used frequencies no higher than 150 MHz, recent advance in detection technology allows direct measurements of amplitude and phase of PDWs of up to 1 GHz. The signal-to-noise ratio (SNR) is mainly influenced by the detector sensitivity and amplification noise. In theoretical and experimental studies it was found that amplitude SNR decreases at higher frequencies, while the phase SNR experiences an optimal value between 400 to 800 MHz [6,7,8].

To optimize imaging-system performance whilst varying multiple parameters is desirable to have a tissue phantom that gives reproducible transillumination results. A tissue phantom can mimic real tissue and can be used to simulate

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different conditions and properties of tissue components in optical imaging studies. Therefore, we have developed a detailed finger joint phantom that allows us to vary tissue parameters typically affected by RA. Here we report on the phantom's development and testing with a frequency-domain measurement system.

II. Methods

A. Phantom Development

There are several ways to develop a reproducible phantom for optical imaging. The main goal is to have tissue-like scattering and absorbing properties in a bulk medium. The bulk medium can be solid or liquid. For simple geometries a liquid phantom with a scattering solution in a container and an additional dye is the easiest way to simulate radiation transport through tissue. But if the bulk medium should have a more complicated geometry, or if certain structures are to be inserted into the bulk medium liquid phantoms have several disadvantages. To mimic complex tissues containers that hold different fluids need to be inserted into each other. A combination of containers suffers from the presence of container walls that usually do not have tissue-like properties and that consequently disturb the radiation transport. In these cases, a combination of solid bodies will give a satisfactory emulation of different tissue components.

In finger joints, the main anatomic structures are: bones, cartilage, tendons, vessels, connective tissue, skin, joint gaps, and the volume between capsule and bone. However, it is not necessary to mimic every component in a phantom. In measurements by Prapavat et al. it was found that in the early stages of inflammation there are changes in the optical properties of the capsule and in the fluid in the joint gap and inside the capsule volume [1]. Furthermore, the volume of the capsule increases and the gap decreases, i.e. the joint is swollen. Therefore the most important components to simulate in a joint phantom are the capsule and the fluid volumes. Considering the main volume fraction, other main components are bones and skin.

To keep the number of parts low, our concept for the phantom was to combine bones, a capsule, a surrounding complex which represents the skin and other soft tissue, a joint gap, and a capsule volume. The outer shape of the finger phantom was a cylinder with a diameter of 20 mm, which is typical for proximal interphalangeal (PIP) finger joints. Furthermore, the asymmetric shape of the bone ends and the capsule was implemented in the phantom design

The material we used for the solid parts of the phantom was silicone (Elastosil® RT 601, Wacker Chemie AG, Germany). This is a two component material that is processed in the liquid phase before it hardens after some hours. Silicone is clear without significant absorption or scattering in the visible and near infrared spectrum with an index of refraction of n = 1.41. The desired scattering effect was achieved by adding TiO_2 powder. Absorbance was adjusted by adding a special silicone dye (Silopren LSR, GE Bayer Silicones, Germany). The joint gap and the volume between capsule and bone were filled with a fluid instead of solid parts because the dimensions were too small. For the fluid we used a clear 60% glycerol in water solution (n = 1.41). Ink (Pelikan 4001 brilliant black) was added to simulate the absorbance change during inflammation.

TABLE I
Optical Properties of Finger Phantom

Component	Absorption coefficient μ_a in mm^{-1}	Scattering coefficient μ_s' in mm^{-1}
skin complex	0.015	1.0
bone	0.04	1.0
capsule:		
non- inflamed	0.08	0.3
inflamed	0.12	0.6
joint fluid:		
non-inflamed	0.007	0
inflamed	0.012	0

Starting from two existing preforms made of resin representing the bones of a PIP finger joint, we built molds out of a synthetic casting compound (Stewalin, hobby time) for bones, capsule and the skin complex. Scattering and absorbing ingredients were added to silicone and every single part was poured and hardened. The remaining elasticity of the silicone aided removal of the parts from the molds without destroying them. The optical properties are shown in Table 1. They were controlled by spectroscopic measurements in an integrating-sphere spectrometer [9]. After assembling the phantom, it was sealed by wrapping a thin, transparent, self sealing film (Parafilm® M) around it twice.

B. Frequency Domain Measurement

The core of the experimental set-up is a vector network analyzer (Advantest Corporation R3765AH, Tokyo, Japan) that serves as modulation source and provides signal analysis for a diode laser and an avalanche photodiode (APD),

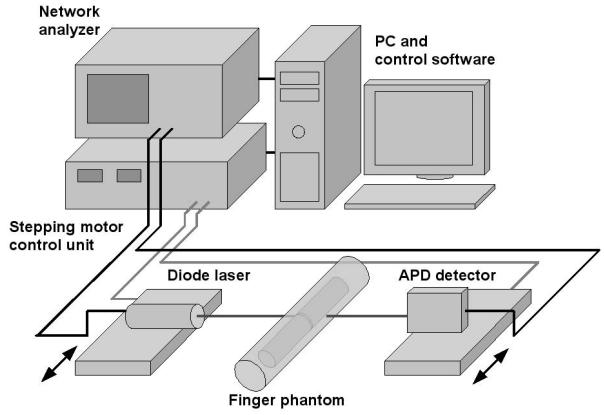

Fig. 1. Scheme of frequency domain set-up. A vector network analyzer serves as modulation source and signal analyzer for diode laser and avalanche photo detector, respectively. Phantom is scanned in sagittal direction.

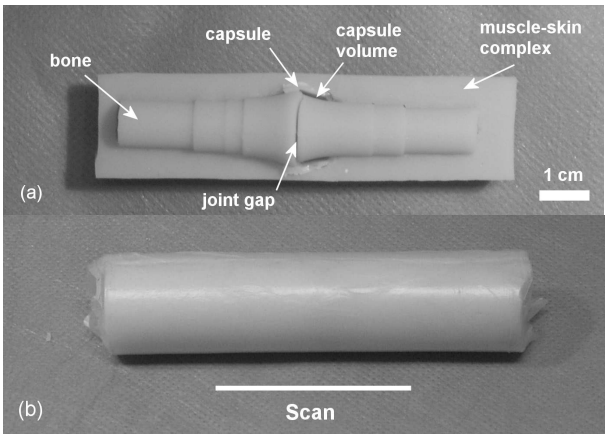

Fig. 2. Joint phantom with several components, (a) upper half of the skin complex removed, distal end (finger tip) of the finger on the left, (b) sealed phantom.

respectively (Fig. 1). The vector network analyzer generates RF signals from 40 MHz up to 3.8 GHz. RF output is directly put into the modulation entrance of the diode laser operating at wavelength 670 nm (LISA laser products OHG, Katlenburg-Lindau, Germany). The modulation power is set to 22 dBm. The collimated beam is restricted by an aperture to a beam diameter of 2 mm. A 1 mm entrance aperture is imaged to the detector by a lens system with a numerical aperture of 0.48. The APD (Hamamatsu C5658), which covers a frequency range of 1 MHz to 1 GHz for measurement of AC modulation and phase, is directly connected to the analyzer. The bandwidth of analysis is set to 10 Hz. Both the laser and detector systems are mounted on a stepping motor translation stage for scanning across the phantom surface. A computer connected via a GPIB bus system serves to control the network analyzer and the stepping motor unit.

The phantom was tested by scanning it coaxially with the laser and detector over the joint region. The complex vector of the modulation signal $Z(\omega) = A(\omega) \exp[i\,\Phi(\omega)]$ was measured at frequencies $\omega = 100$ MHz and 500 MHz and amplitude A and phase Φ were calculated. At each position the measurement was repeated ten times and averaged. To test the reliability of the phantom composition, the phantom was scanned seven times and disassembled and reassembled between the scans. The dark signal was subtracted by vector subtraction. Amplitude and phase are corrected for the system transfer function by measuring the signal of a neutral density filter as a reference and by vector division of phantom and reference signal. We simulated two different stages of RA by varying the optical properties of the capsule and of the joint fluid from non-inflamed to inflamed.

III. Results and Discussion

The phantom is shown in Fig. 2. The solid phantom parts are stable and can be reassembled repeatedly. The parts fit together very well and there are no unwanted gaps. The steps at the bone surface are from turning the preform and facilitate assembling the phantom. The glycerol solution is

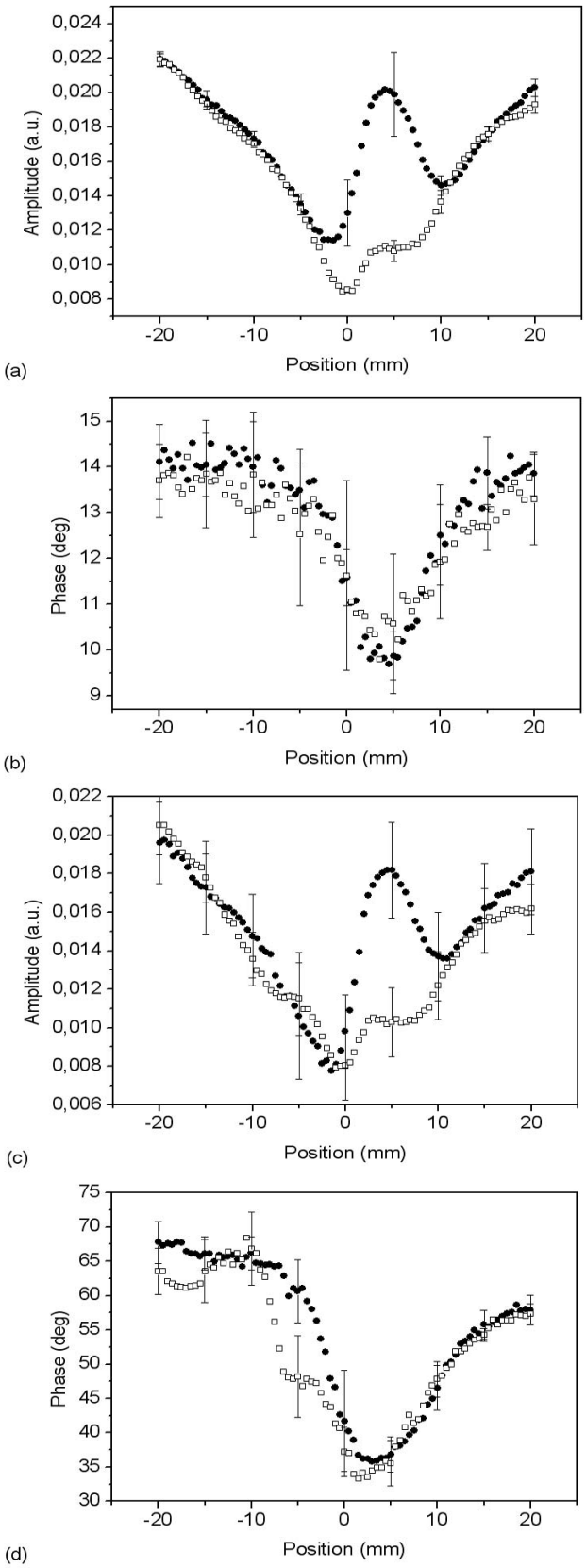

Fig. 3. Coaxial scan over the finger joint phantom, amplitude (a, c) and phase (b, d) for non inflamed (dots) and inflamed (empty squares) stage at 100 MHz (a, b) and 500 MHz (c, d). Error bars are standard deviation from seven times reassembling of the phantom.

filled into the gaps and displaces any air. Thus, the index of refraction is perfectly matched and is homogeneous over the entire phantom.

Scanning over the phantom shows some characteristic behaviour in amplitude and phase (Fig. 3). The general trend in the amplitude is a drop to the middle of the joint (Fig. 3a, c). In the healthy, i.e. non-inflamed stage, there is a pronounced rise in the region of the capsule, whereas in the inflamed stage there is only a slight increase in this region. The phase clearly decreases in the joint region (fig. 3b, d). Because damping of modulation depends more on absorption than on scattering, the reason for the amplitude drop in the middle should be the increasing diameter of the bone and its higher absorption compared to the surrounding material. In contrast, the low absorbing fluid in the capsule volume causes the rise in the capsules region, whereas in the diseased stage the higher absorption in the capsule and fluid reduces this rise. Phase indicates the time delay or path length. Therefore it mainly depends on changes in scattering. As bone and the skin complex have the same scattering coefficient, the drop in phase occurs because of the non-scattering fluid in the capsule volume and the joint gap. It seems that phase at 100 MHz decreases a little less in the inflamed stage, but the differences are well within the error. In general, the increase in scattering in the capsule becomes noticeable. Switching to 500 MHz, the signal becomes noisier. In the amplitude the signal behaviour is quite the same as at 100 MHz. In phase, beside the expected increase in phase shift (now ~35-65 degree compared to ~10-14 at 100 MHz) with increasing frequency, there is now at some locations (e.g. at –5mm) a statistically significant difference between the healthy and inflamed joint.

Reassembling of the phantom causes a signal deviation in the joint region of about 10 to 20 %. Nevertheless, the inflamed stage is clearly distinguishable from the non-inflamed stage.

IV. Conclusion

We showed that realistic complex tissue structures can be realized in a tissue phantom by employing solid silicone parts. Using this approach we developed a model of a finger, which allows to vary optical properties within the joint as they are typically encountered in healthy finger joints and joints affected by rheumatoid arthritis. We used the phantom in initial studies with a frequency-domain measurement system, and found that affected and healthy joints can be distinguished in their amplitude signal. Differences in the phase signal between the two types of joints only become apparent at higher frequencies (here 500 MHz).

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References

[1] V. Prapavat, W. Runge, J. Mans, A. Krause, J. Beuthan, and G. Mueller, "Determination of optical tissue parameters of joint system at an early stage of rheumatoid arthritis (in vitro)," *Minimal Invasive Medizin,* vol. 8, no. 1-2, pp. 7-16, 1997.

[2] J. Beuthan, O. Minet, G. Müller, and V. Prapavat, "Infrared diaphanoscopy in medicine," in *Medical Optical Tomography: Functional Imaging and Monitoring,* G. Müller, B. Chance, R. Alfano, S. Arridge, J. Beuthan, E. Gratton, M. Kaschke, B. Masters, S. Svanberg, P. van der Zee, Eds. Bellingham, Washington: SPIE, 1993, pp. 263-282.

[3] A. K. Scheel, A. Krause, I. Mesecke-von Rheinbaben, G. Metzger, V. Rost, V: Tresp, P. Mayer, M. Reuss-Borst, and G. A. Müller, "Assessment of proximal finger joint inflammation in patients with rheumatoid arthritis using a novel laser-based imaging technique", *Arthritis Rheum,* vol. 46, pp. 1177–1184, 2002

[4] A. D. Klose, A. H. Hielscher, "Iterative reconstruction scheme for optical tomography based on the equation of radiative transfer", *Med Phys,* vol. 26, pp. 1698–1707, 1999.

[5] A. K. Scheel, M. Backhaus, A. D. Klose, B. Moa-Anderson, U. J. Netz, K.-G. A. Hermann, J. Beuthan, G. A. Müller, G. R. Burmester, and A. H. Hielscher, "First clinical evaluation of sagittal laser optical tomography for detection of synovitis in arthritic finger joints", *Ann Rheum Dis,* vol. 64, no. 2, pp. 239-245, 2005, epub ahead of print 2004 Aug. 5.

[6] D. A. Boas, M. A. O'Leary, B. Chance, and A. G. Yodh, "Detection and characterization of optical inhomogeneities with diffuse photon density waves: a signal-to-noise analysis," Appl. Opt., vol. 36, pp. 75-92, 1997.

[7] V. Toronov, E. D'Amico, D. Hueber, E. Gratton, B. Barbieri, and A. Webb, "Optimization of the signal-to-noise ratio of frequency-domain instrumentation for near-infrared spectro-imaging of the human brain," Opt. Exp., vol. 11**,** 2717-2729, 2003. Available: http://www.opticsexpress.org/abstract.cfm?URI=OPEX-11-21-2717

[8] X. Gu, U. Netz, K. Ren, J. Beuthan, and A. H. Hielscher, "Sensitivity Analysis for Frequency Domain Optical Tomography of Small Tissue Volumes", presented at the OSA Biomedical Optics Topical Meeting, Fort Lauderdale, USA, March 19-22, 2006, Paper MH1

[9] A. Roggan, O. Minet, C. Schröder, and G. Müller, "Measurements of Optical Tissue Properties Using Integrating Sphere Technique", in *Medical Optical Tomography: Functional Imaging and Monitoring*, Müller G., Chance B., Alfano R. et al., Eds., Bellingham, Washington: SPIE, 1993, pp. 149-165.