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Abstract. Conventional imaging modalities are unable to depict the early degeneration of articular cartilage in osteoarthritis, especially in small joints. Optical coherence tomography has previously been used successfully in high-resolution imaging of cartilage tissue. This pilot cadaver study demonstrates the use of intra-articular optical coherence tomography in imaging of articular cartilage of the first carpometacarpal joint, producing high resolution images of the articular surface in which cartilage thickness and surface characteristics were assessed. Findings on optical coherence tomography were confirmed with histology. Furthermore, co-registration of optical coherence tomography and computed tomography was used to accurately determine the scanned trajectory and reconstruct a true-scale image overlay. © 2012 Society of Photo-Optical Instrumentation Engineers (SPIE). [DOI: [10.1117/1.JBO.17.6.060501](https://doi.org/10.1117/1.JBO.17.6.060501)]

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1 Introduction

Osteoarthritis (OA) of the hand is a common cause for pain and disability in Western populations. At the age of 60 years, hand OA is prevalent in about 40% of people.¹ The first carpometacarpal joint (CMC-1) is the second most frequent location of

hand OA² and a major cause for pain and disability in patients suffering from OA.³

The hallmark feature of OA is degeneration of articular cartilage that lines the synovial joints, with accompanying inflammatory reaction of the synovial membrane and underlying bone. Visualizing this degeneration of articular cartilage, especially in early OA, remains a challenge to date. Nearly half of patients with radiologic evidence of OA do not suffer from symptomatic disease.⁴ On the other hand, a considerable amount of patients experience complaints attributable to OA, without radiologic evidence to support the diagnosis. In these patients, detailed information on the state of the cartilage tissue may provide the clinician with a more profound basis to determine a therapeutic strategy.

In part, the discrepancy between clinical and radiological features can be explained by the fact that to date, conventional cross-sectional imaging like computed tomography (CT) and magnetic resonance imaging (MRI) has not been able to depict the changes in articular cartilage as seen in early OA.

The use of optical coherence tomography (OCT) in high-resolution imaging of early changes in osteoarthritic articular cartilage, like surface fissuring, fibrillation and local erosion, has previously been described in large joints like the knee.^{5–8} Moreover, OCT has been utilized during arthroscopic surgery in large joints to assess articular cartilage *in vivo*, in both animal models⁹ and human subjects.^{5,7,8} So far, *in-situ* OCT assessment of smaller joints of the wrist has not been attempted because suitable probes were not available. In recent years, developments in OCT have yielded OCT systems utilizing thin endoscopic probes originally devised for use in intravascular imaging in the field of cardiology.^{10–12} These developments alongside with the clinical impact of OA of the CMC-1 joint motivates our present study to examine the proof of principle of minimal invasive intra-articular OCT of articular cartilage of the CMC-1 joint in a pilot cadaver study that is approved by our institutes internal review board. In this experimental setup, intra-articular OCT was combined with CT studies with the OCT probe *in-situ* to facilitate orientation of the OCT images and establish the correct orientation for production of histologic slides for reference. Moreover, the use of CT enabled co-registration of OCT and CT data to produce a fused dataset with which an image overlay of the cartilage on OCT and segmented bone on CT images was constructed.

2 Methods

A fresh-frozen post-mortem human wrist was stored at 4 °C for three days prior to imaging to re-gain flexibility of the joints. An 18-gauge MicroLance[®] iv-cannula was introduced into the CMC-1 joint on the dorsal side of the joint. The needle was removed and the OCT probe inserted through the cannula into the joint. After reaching the joint cavity, the iv-cannula was retracted and OCT scanning is performed.

OCT images were recorded using a commercially available C7-XR[™] Intravascular Imaging System interfaced to a C7 Dragonfly[™] Intravascular Imaging Probe (St. Jude Medical, St. Paul, Minnesota, USA). This fiber-optic OCT system with an outer probe diameter of 2.7 Fr (0.9 mm) produces cross-sectional images with an axial resolution of 15 μm and a lateral resolution of 30 to 35 μm at 1300 nm. The automatic pullback system scans across a trajectory of 520 mm along the probe in

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approximately 5.5 s, producing a 540 frame dataset. This results in a total scanned cylindrical volume of 520 (length) by 10 mm (diameter) with an imaging depth of about 1.5 mm.

High-resolution CT images were acquired with the OCT probe *in-situ* using a 64-slice CT scanner (Brilliance CT 64 Channel, Philips Medical, Eindhoven, The Netherlands). A standard protocol for upper limb cadaver CT scans was used with the following parameters; collimation 64×0.625 with a tube charge of 120 kV, slice thickness of 0.67 mm, image matrix of 512×512 pixels, pitch 0.2 and field of view 169 mm.

After completing both OCT- and CT scanning, the OCT probe was removed and the cadaver wrist was refrozen at -80°C in preparation for histologic processing. OCT and CT data were analyzed and reconstructed in 3D to identify the plane of sawing for histologic processing. From the deep frozen specimen and after careful consideration of the reconstructed 3-D images, the entire CMC-1 joint was excised by our expert pathologist (JB) in 4 mm thick serial slabs using a butcher bandsaw (Kolbe K430), while approaching the previously established orientation as much as possible, perpendicular to the direction of the OCT probe. After fixation in 10% formalin, the slabs were decalcified in formic acid (10%)—sodium formate (Kristensen) and $4 \mu\text{m}$ Hematoxylin-eosin stained slides were made.

Images were visualized and reconstructed using Amira visualization software (Amira®, Visage Imaging, San Diego, CA). Where necessary, we segmented bone structures on CT slices manually. To view and reconstruct DICOM data, the open-source DICOM reader OsiriX was used. Also, Co-registration of CT and OCT images was performed using custom-made software. DICOM data of a matching CT- and OCT scan were utilized for fusion between the two modalities. Data was resampled for display in identical voxel sizes, enabling a true scale overlay of the images. Images were co-registered manually in three planes, using landmarks that can be identified on both modalities, such as the OCT probe and its position, the shape of the intra-articular space, air bubbles and regions of soft tissue. Co-registered images were visualized with false color overlay of the OCT data and segmented bone structures on CT.

3 Results

The joint cavity of the CMC-1 joint with the joint surfaces of the trapezium and the first metacarpal bone are visualized on the OCT images (Fig. 1). Soft tissue is visible flanking the articular surface of the joint. In most images, the cartilaginous layer and the transitional zone between subchondral bone and cartilage is identified. In general, the cartilage layer on the first metacarpal bone appears more prominent compared to the layer on the trapezium. Cartilage thickness is measured between 0.6 and 1.1 mm on images in which the cartilage layers are identified clearly, to be compared with findings on histology. Cartilage appears relatively smooth with local fibrillation of both cartilage layers. Also, the layer on the trapezium shows local erosive changes with loss of layer thickness, which is more prominent on the radial side of the joint compared to the ulnar side (Fig. 1).

Images acquired with CT are reconstructed in 3-D to accurately depict the (intra-articular) trajectory of the OCT probe for reference (Fig. 2), especially to determine the correct orientation for histologic processing. The OCT probe trajectory as visualized with CT and image features apparent in both CT and OCT datasets, such as intra articular space, are used for co-registration, resulting in a multimodal fused dataset. The

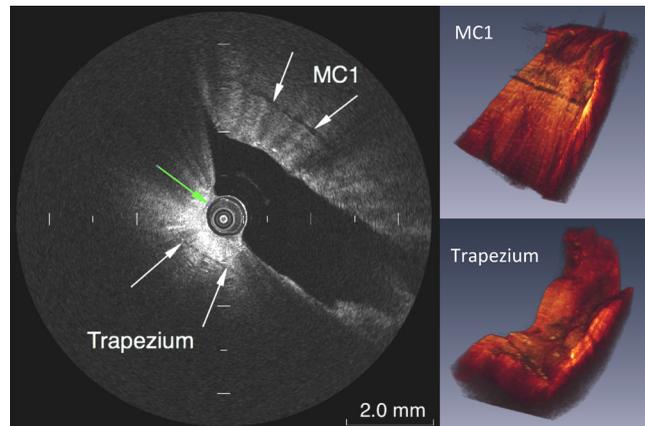


Fig. 1 Intra-articular OCT image, transverse orientation. Clearly visible transitional zone between cartilage and bone (white arrows) on both the trapezium and the first metacarpal bone (MC1). The cartilage layer is thicker on the metacarpal side of the joint, with some surface fibrillation and irregularity, which can be seen clearly in the 3D reconstructed en-face images of the MC1 and trapezium surfaces (right upper and lower).

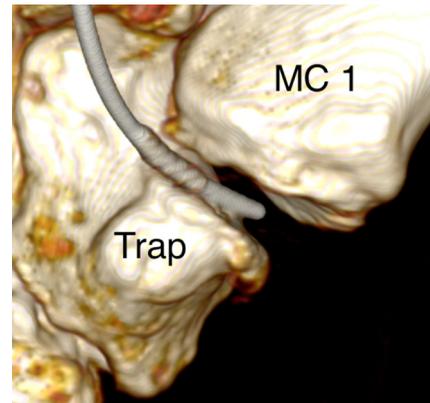


Fig. 2 CT snapshot of the CMC-1 joint, 3-D volume reconstruction. The image accurately depicts the intra-articular trajectory of the OCT probe. Trap: trapezium, MC1: first metacarpal bone.

co-registered images clearly display the cartilage layers as seen on OCT outside the CT bone segmentation limits, marking the location and thickness of the cartilaginous layer adjacent to the bony structure, that cannot be seen on CT alone (Fig. 3).

Histologic slides are shown in Fig. 4, the articular cartilage of the trapezium shows a striking decrease in thickness compared to the adjacent metacarpal bone, corresponding with findings on OCT. Local erosion and fissuration of cartilage is seen which is more prominent in the joint surface of the trapezium compared to the surface of the first metacarpal bone. Maximum measured cartilage thickness throughout the histologic slides is 1.1 mm (Fig. 4). This confirms the results found on OCT, concerning the thickness and surface characteristics of the cartilaginous layers of the CMC-1 joint.

4 Discussion

In this pilot study, we successfully visualized articular cartilage of the CMC-1 joint using intra-articular fiber-optic OCT, which has never been reported so far. Moreover, information about the cartilage layer in terms of thickness, and surface characteristics like fibrillation and local erosion, could be assessed and

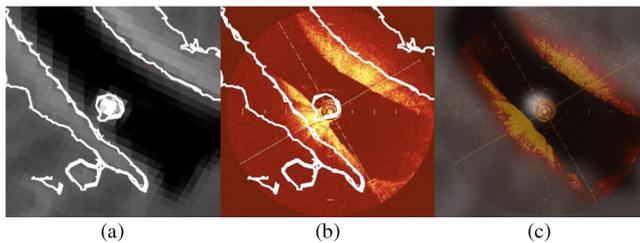


Fig. 3 Co-registration between CT and OCT, transverse orientation. (a) CT detail with segmented probe and bone structures (white lines). (b) OCT overlay on bone segmentation data. Note how the OCT data exceeds the boundaries of the CT segmentation, signifying the location of the cartilage layer. (c) Co-registered OCT/CT image without segmentation overlay with decreased opacity of CT data.

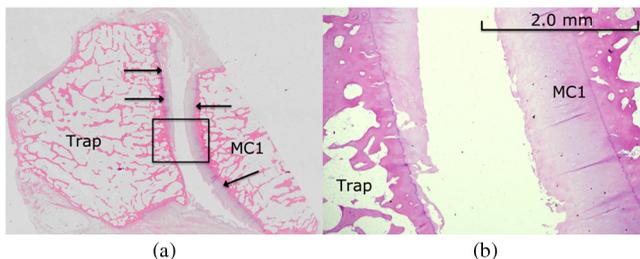


Fig. 4 Histology of the CMC-1 joint (Hematoxylin/Eosin staining). (a) overview image in which the articular cartilage of the trapezium and MC1 are marked by arrows. (b) Detail image of the articular surface (rectangle in left image), 20x magnification. Note the thinner cartilage layer on the surface of the trapezium (Trap) with more pronounced erosive changes compared to the articular surface of the first metacarpal bone (MC1).

confirmed with histology. The minimal invasive approach of the joint through an iv-cannula, combined with the use of a thin probe, makes application of this technique in a clinical setting possible in the nearby future.

Because no direct en-face view of the cartilage surfaces was acquired in this experiment, macroscopic assessment of the scanned surfaces was not performed. However, reports have shown that OCT imaging may detect changes in cartilage tissue earlier compared to macroscopic assessment during arthroscopy.¹³ Moreover, analysis of birefringence using polarization sensitive OCT allows real time quantitative assessment of the articular cartilage matrix.^{14,15}

Co-registration of CT and OCT images facilitates orientation of the OCT images inside the joint cavity. More importantly, it allows visualization of the cartilage layer on OCT by overlaying the images upon segmented CT data, which greatly enhances the value of the recorded scans. Co-registration of OCT and CT images has not been reported so far. In this experimental setup, co-registration between the slightly curved trajectory of the flexible OCT probe tip on CT and the rigid (cylindrical shaped) OCT data was pursued. Nonetheless, a very good registration between the CT and OCT images was acquired. In the future, however, this may even be improved by using newly developed software and hardware that enables deformable registration of the two imaging modalities in 3-D.¹⁶

Histologic assessment played an important role in determining the feasibility of this experimental setup. Matching orientation and location of the histologic slides with landmarks as seen on OCT was complicated. In this pilot however, morphologic

assessment of cartilage and subchondral bone on the histologic slides supported our findings on OCT concerning the cartilage layers of the CMC-1 joint.

5 Conclusion

In conclusion, our proof of principle study demonstrates the technical feasibility of assessing articular cartilage of the CMC-joint *in-situ* and in high resolution utilizing a thin, fiber optic OCT probe. Cartilage OCT may enhance the quality of information available to the clinician in patients with early CMC-1 OA and with it, bring a new approach to therapeutic decision-making.

Moreover, the combination with high resolution CT and subsequent fusion of CT and OCT images is considered a leap forward in cartilage imaging and brings perspective to future cartilage OCT research in which OCT may be compared to other (non-invasive) imaging modalities.

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