Non-invasive 3D imaging of the human carotid artery with volumetric multispectral optoacoustic tomography (vMSOT)

By I. Ivankovic & Prof. D. Razansky

The majority of ischemic strokes are caused by atherosclerotic carotid arteries, specifically in the carotid bifurcation area [1]. Much effort in stroke prevention is directed towards early diagnostic or screening methods that could categorize patients as either high or low risk. In such screening methods it is essential to characterize the stability of any atherosclerotic plaque rapidly and in a non-invasive manner.

OPTOACOUSTIC IMAGING

OA imaging has attracted much attention in recent years because of its potential applicability to a range of biological and medical imaging applications. OA is based on the use of non-ionising laser light, which is absorbed by biomolecules at specific wavelengths, creating a transient thermoelastic expansion which results in acoustic waves being emitted that can be detected by an ultrasound transducer. OA imaging can therefore provide images of high optical contrast with spatial resolution equivalent to that of typical ultrasound devices. OA imaging is particularly powerful in the near-infrared (NIR) window, since such light can penetrate deeper into human tissue. In the NIR wavelength range, oxygenated and deoxygenated hemoglobin have different absorption spectra, thus allowing the discrimination of veins and arteries in the human body. In addition, lipids, water and melanin also have strong absorption in the NIR wavelength window, so offering a multispectral optical contrast image of living tissue [2]. For these reasons, OA imaging, and in particular imaging of the human vasculature has become an extremely active area of research and development.

The potential of the emerging imaging modality of Multispectral optoacoustic tomography (MSOT) has been described in recent clinical studies where MSOT has shown its capability to image tissues in diseases such as breast cancer [3] and inflammatory bowel disease [4]. OA imaging has also been shown capable of imaging atherosclerotic disease by utilising the absorption spectrum of lipids, which is a key constituent of vulnerable plaques. *Ex vivo* studies have shown that by imaging at 1200nm a clear identification of plaque in human aorta is possible [5]. *In vivo* intravascular studies using an endoscopic device have demonstrated vulnerable plaque detection in rabbits [6]. (Of course endoscopy is an invasive procedure and is not suitable for screening).

vMSOT EVALUATION STUDY

We carried out an evaluation study whose goal was to investigate the feasibility of using volumetric MSOT in clinical imaging of the human carotid artery [7]. In this study we used a custom-designed probe, composed of a spherical surface array capable of isotropic 3D resolution of 200µm [Fig. 1 (A)], [8]. The probe has a central opening to allow the laser output to pass through the fibre bundle connecting the probe to the laser. A surface array containing 256 piezoelectric elements detects the acoustic signal. The OA signals that are generated are simultaneously acquired by a custom-built parallel data acquisition system.

To evaluate the system, we recruited 16 healthy volunteers for non-invasive imaging of the carotid bifurcation.

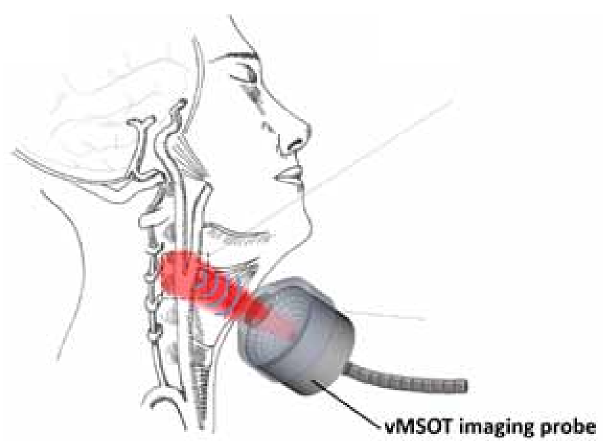

Figure 1. The imaging set up.

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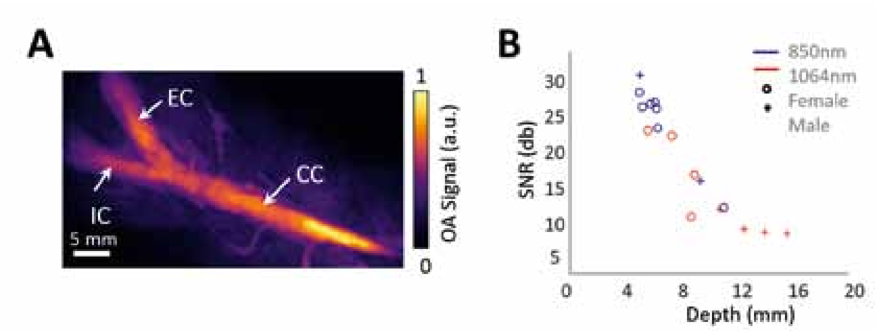

Figure 2 (A) Compounded image of scan of entire carotid artery (B) SNR plotted against carotid depth (IC; internal carotid, EC; external carotid, CC; common carotid, SNR; signal to noise ratio)

The volunteers were imaged in the NIR wavelength range between 730-900nm and 1064nm, in compliance with the safety standards of the American Laser Institute [9]. Within one single laser pulse, an entire volumetric image (20mm x 20mm x 20mm) of the carotid bifurcation could be acquired [Figure 1B]. Initially the handheld probe was moved freely around the carotid bifurcation area and, once the desired region was located, the probe was held stationary for optimal image acquisition.

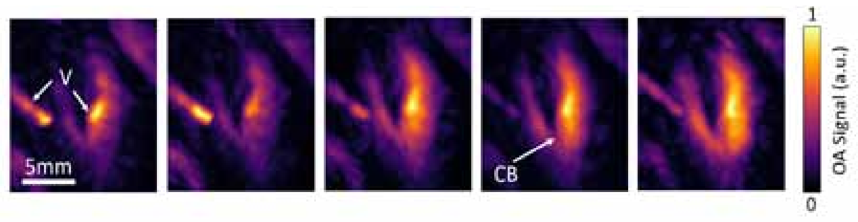

Figure 3. Volumetric MSOT images of right carotid artery bifurcation at a wavelength range between 730-900nm (V; vein, CB; carotid bifurcation)

RESULTS

The scanned data sets consisted of multiple 3D images, which were stitched together by means of a spatial compounding algorithm, allowing for visualisation of the scan (area of $45mm^2$) of the carotid artery in one single image. The common carotid (CC), internal carotid (IC), external carotid (EC) and other small surrounding vessels can all be seen at the same time [Figure 2A].

The depth of the carotid arteries was measured in all volunteers, and lay between 4-16mm depth from the skin surface. The signal to noise ratio (SNR) was subsequently calculated. and plotted against the depth of the carotid for all volunteers. It could be seen that there was a clear decrease in SNR in deeper carotid arteries, mainly attributable to light attenuation [Figure 2B].

Five volunteers were then imaged at wavelengths between 730-900nm for multispectral evaluation. It was found that the carotid artery was best visualised between 800-900nm, corresponding to the increased absorption of oxygenated hemoglobin and decreased absorption of deoxygenated hemoglobin [Figure 3]. The differentiation between arteries and veins is striking when the appropriate wavelength is used for OA imaging. Multispectral evaluation is critical in demonstrating the capabilities of MSOT. and is particularly so in detecting lipid rich vulnerable plaques, where lipids have a peak absorption at 1200nm.

Anatomical features resolved from MSOT were validated against ultrasound (US) images in two volunteers, where the carotid arteries were scanned by an experienced vascular surgeon using a clinical B-mode ultrasound scanner. Whereas the entire carotid bifurcation area could be readily visualized with volumetric MSOT thanks to its three-dimensional imaging capabilities, it was not easily discernible in single cross-sectional US images. In fact, US visualization of the whole carotid bifurcation in a single cross-section usually requires a lengthy acquisition time to find the optimal orientation of the US probe. In contrast, a similar view can be directly obtained from the three-dimensional optoacoustic image.

CONCLUSION

Overall, our study demonstrates the potential of volumetric multispectral optoacoustic tomography for the characterisation of the carotid artery in a volumetric, non-invasive, real-time and handheld manner. Multispectral optoacoustics has the ability to identify clinically relevant biomarkers such as lipids, which are a key feature in vulnerable plaques. Our studies show that volumetric MSOT has a high potential for the non-invasive and functional assessment of cardiovascular disease.

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