Modalities of photothermal coherence tomography for enhanced three-dimensional imaging contrast, resolution and quantitative depth profilometry

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Introduction – Photothermal coherence tomography (PCT) enables thermal waves to exhibit *energy localization* akin to non-diffusive waves like ultrasound, despite their diffusive nature. It uses laser-pulse-induced thermal excitation and performs pulse compression and matched filtering, two encoded waveform processes inspired by radar science. In the enhanced truncated correlation (eTC-PCT) modality of PCT, time-windowed thermal diffusion transient signals are cross-correlated with the delay-shifted reference signal and used to reconstruct slice-by-slice depth distribution of optical and thermal sources in opaque and multi-absorber solids.

I. Spatially filtered PCT for enhanced spatial resolution imaging – A unique spatial gradient-window adaptive thermophysical filter was introduced [1] in a scanned mode along the *(x,y)* coordinates of camera images from various sub-surface depths, revealing absorber true spatial extent from diffusive photothermal images and restoring pre-diffusion lateral image resolution beyond the Rayleigh criterion limit in diffusion-wave imaging science. An example is shown in Fig. 1.

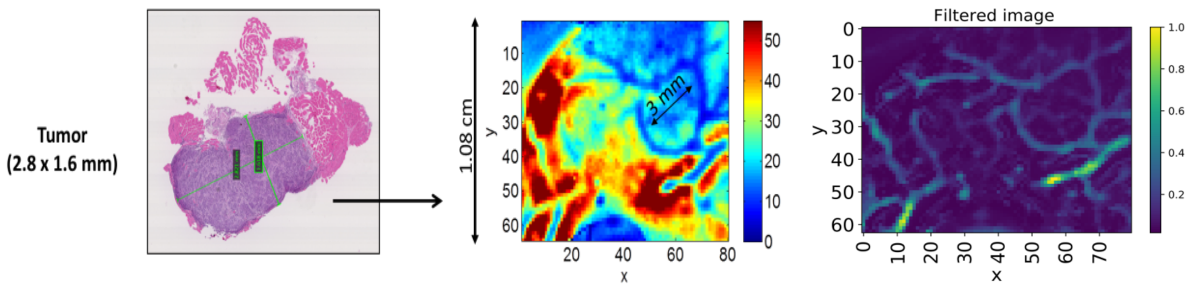

Fig. 1: (a) Immunohistochemistry stain of tumor cells surrounded by normal muscle cells in a mouse thigh. **(b)** eTC-PCT phase image shows the tumor with size of 2.8 mm and the vascular network around the tumor in dark blue. **(c)** Filtered image of combined eTC-PCT amplitude and phase reveals the presence of smaller vessels.

II. Image segmentation using K-means clustering for enhanced feature boundary imaging – K-means is an iterative algorithm that aims to partition a dataset into K pre-defined distinct non-overlapping subgroups (clusters) where each data point (datum) belongs to only one group. In PCT non-destructive imaging, K is initialized by selecting 3 distinct areas: 1) The area of the defect or the inhomogeneity; 2) the area with higher thermal-wave accumulation due to encompassing a defect or an inhomogeneity; and 3) a remote (reference) area away from the defect. The next step after preparing a *Segmented Image (SI)* is to detect edges and delineate the boundary/ies of the defect or inhomogeneity. Furthermore, the Canny edge detection algorithm is one of the most strictly well-defined methods that provides good and reliable detection of subsurface region-of-interest (ROI) edges [2]. Fig. 2 shows the effects of applying these algorithms to PCT imaging, resulting in sharp boundary delineation of defect boundaries.

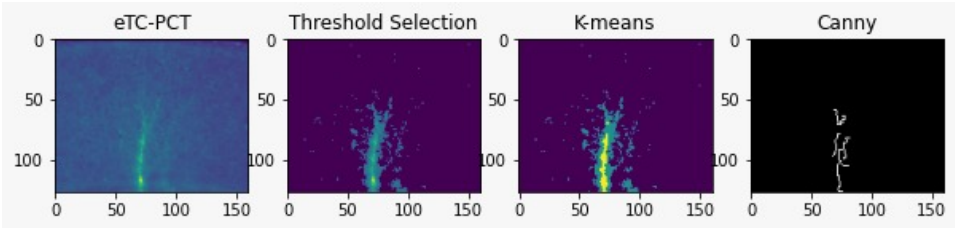

Fig. 2: eTC-PCT images of a surface-terminating crack in a steel sample. The raw eTC-PCT images of the crack are presented before processing and after threshold selection (step 1), K-means clustering (step 2); and the final canny edge detection (step 3). The result is a crack image reconstruction with sharply delineated boundaries.

III. Multispectral Pulsed PCT for enhanced contrast and quantitative depth profilometry imaging – To obtain molecular specificity in biological samples we introduced multispectral (MS) PCT that employs a Nd:YAG pulsed laser which pumps an optical parametric oscillator (OPO) for wavelength tunability, Fig. 3 [3]. As a first application, the quantitative detection of early stage caries in photothermal images of teeth using MS eTC-PCT is reported.

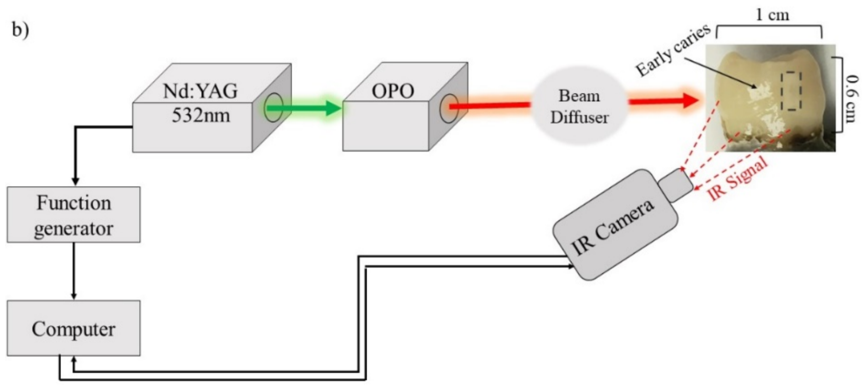

Fig. 3. Experimental configuration of multispectral eTC-PCT system and photograph of a tooth sample with early caries.

An extracted healthy tooth was used in this study, as can be seen in Fig. 3. To closely mimic the natural formation of dental caries, a treatment protocol using highly cariogenic bacteria was used to produce a carious lesion. The bacterial-induced caries was limited to a rectangular section on the smooth surface of the tooth for a total exposure time of 8 days to induce early caries. As a result, the overall appearance of the extracted tooth in visible light remained unchanged. These data were either directly used for 3D reconstruction through ImageJ software [4] or imported into MATLAB 2021a for data analysis (e.g. normalization and SNR calculation) of the images obtained from the TC-PCT amplitude and phase channels.

Fig. 4 shows the MS eTC-PCT amplitude reconstructions of the investigated tooth at 0.5 Hz single repetition frequency and at OPO wavelengths 532 nm, 675 nm, 700 nm, 750 nm, 808 nm, 850 nm, and 900 nm. The location and extent of the lesion in the tooth is seen in the top cross-sectional views, with the 0.5-Hz repetition frequency at 675-700 nm offering the optimal visualization of the subsurface extent of the caries. Aside from the bacterial-induced caries, one can see another carious region highlighted by the red arrow that is only captured by the 532-nm wavelength. We concluded that this carious region is positioned very close to the surface that only one highly scattered wavelength, i.e. 532 nm, is able to capture this feature. Micro-computed tomography (μCT) analysis of the deep lesion showed it is indeed a deeper lesion compared to other defects on the tooth with an approximate depth of 400 μm, in agreement with the depth profile reconstructed from the 675 nm and 700 nm images.

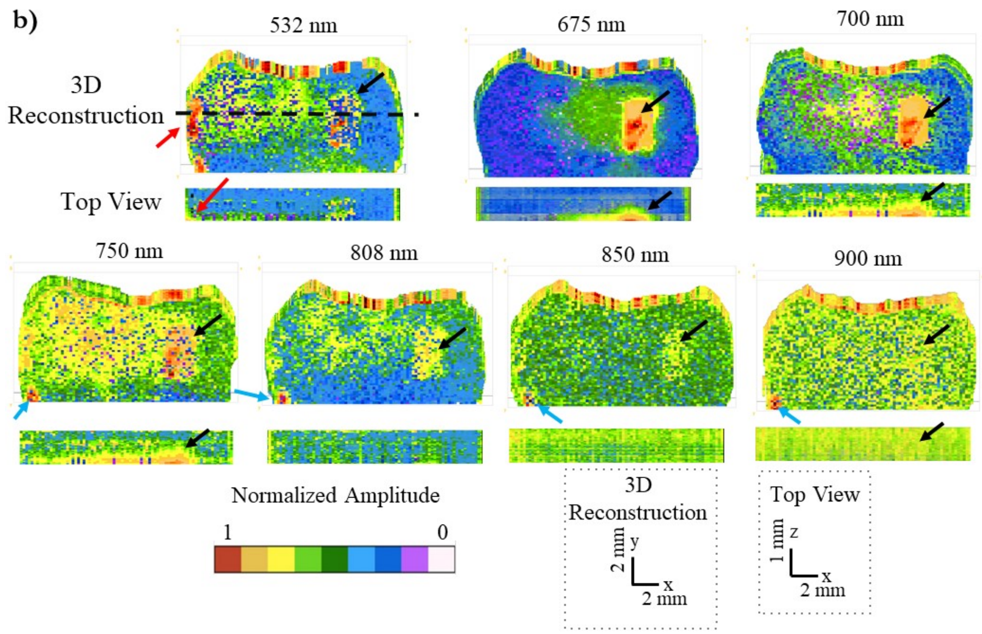

Fig. 4. 3D eTC-PCT amplitude reconstruction of a carious lesion in a tooth sample taken at 0.5 Hz and pulsed Nd:YAG laser OPO wavelengths 532 nm, 675 nm, 700 nm, 750 nm, 808 nm, 850 nm, and 900 nm. Below each 3D reconstruction, the top view of the cross-section of the reconstructed 3D model is shown, cut along the dashed black line, as marked in the 532-nm 3D reconstruction. The extent of the lesion inside the tooth is seen in the top view of the cross-section. Note that the x- and z-axis scales are different in the 3D reconstruction and the top view for better visualization. The bacterial-induced caries is shown by a black arrow in each reconstruction. Red and blue arrows identify a shallow and a deep natural lesion on the tooth, respectively.

Conclusions – This talk reports on the implementation of three PCT imaging modalities and explores their impact in spatial resolution, feature/defect boundary delineation, contrast and quantitative depth profilometry in photothermal/theorphotonic applications ranging from soft and hard tissue imaging to non-destructive testing of manufactured materials with defects.

References

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