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OCT as tool for laser ablation monitoring applied to cholesteatoma

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I. INTRODUCTION

Cholesteatoma is an accumulation of exfoliated keratin from squamous epithelium that invades the middle ear, erodes the bony structures, and causes hearing loss as well as other serious complications. The only treatment of this disease is surgical intervention. As the middle ear cavity is small and contains hidden recesses, the complete removal of the disease is still challenging and the recurrence rate can reach 25% for conventional methods. An advanced treatment for this disease is laser surgery that has been proven to remove efficiently the residual cholesteatoma, thus reducing the recurrence rate [1]. In the µRoCS project[1], we aims to propose a dexterous continuum robot with embedded laser instrument for exhaustive cholesteatoma removal. As part of this project, this study focuses on measuring the vaporized volume of cholesteatoma during the laser ablation process depending on the laser parameters. This volume will be obtained using OCT scanning and the proposed image processing. The result has an important role to vaporize the right amount of cholesteatoma tissue as insufficient removal would result in cholesteatoma recurrence and excessive removal would damage the healthy structures nearby.

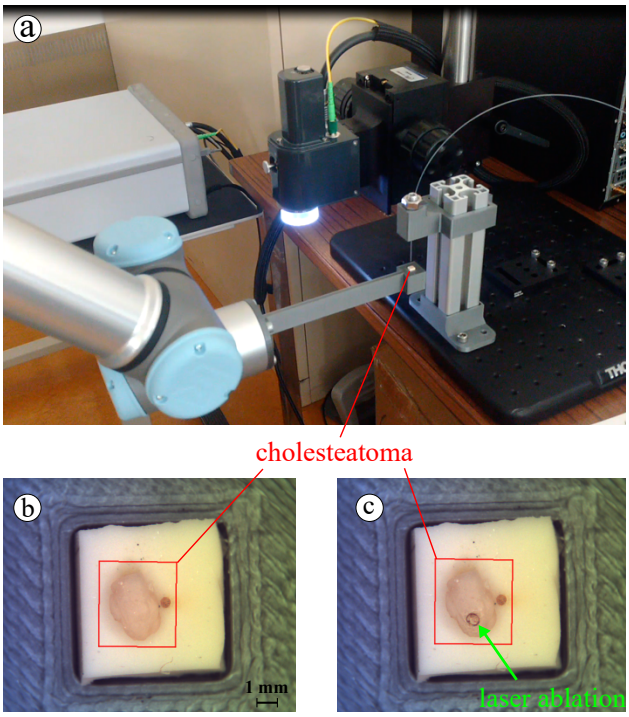


Fig. 1: (a) Experimental Setup. (b) Cholesteatoma before and (c) after a laser ablation.

II. MATERIALS AND METHODS

A. Experimental setup

An LBO fibered laser (Velas-8G, 532 nm, 8 W) was employed to vaporize cholesteatoma samples collected from Besançon Hospital[2] (see Fig. 1). The optical fiber has a core diameter of 400 µm and a numerical aperture of 0.22. The studied parameters are the laser power (6 W and 8 W) and the exposure time (100 ms to 250 ms). The distance between the fiber tip and the tissue is important due to the divergence of the exiting laser beam. It should be as short as possible so the size of the laser spot is minimal. A small laser spot allows for precise ablation while limiting the unwanted heating of surrounding tissues. The fiber tip is manually positioned in contact with the sample before each laser pulse. The distance is therefore considered constant throughout the study. Then, the tested laser pulse was shot to vaporize a small amount of cholesteatoma tissue. To estimate this vaporized volume, 3d-images (C-scan) of the sample were acquired using a TELESTO-II OCT with an LSM03 probe. The voxel dimensions were 25 µm along the X and Y axes and 3.5 µm along the Z axis (optical axis). Eventually, a UR3 collaborative robot arm was used to sequentially position the sample under the laser instrument and the OCT.

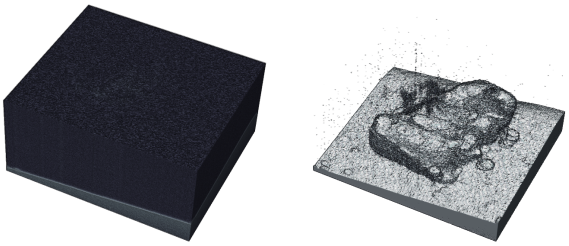
B. Cholesteatoma segmentation

The main phases of the cholesteatoma segmentation are presented in Fig. 2. First, a threshold is applied to roughly separate the volumes of matter (cholesteatoma and support) from the background (Fig. 2b). In order to remove

*Q. Boyer and D. V. A. Nguyen contributed equally to this work.

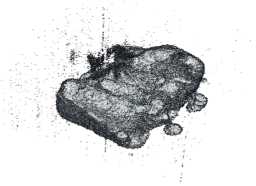
[1]https://anr.fr/Project-ANR-17-CE19-0005

[2]The samples used are human surgical wastes collected under ethical approval.

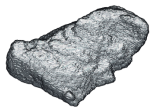


(a) Initial image.

(b) Binarized image.



(c) After support removal.



(d) Final image for volume estimation.

Fig. 2: Steps of cholesteatoma OCT image processing.

the support, we extract from the obtained image two arbitrary cross-sections parallel to the $(0xz)$ plane that only contain the support element, not the tissue (e.g., at the boundaries of the image). The outlines of these cross-sections are then obtained using the Canny edge detector (*edge* function in Matlab). As the support has a prismatic shape, it's surface can be approximated by performing a linear interpolation between the outlines detected in the previous step. This can then be used to subtract the support from the binary image obtained after thresholding. At this stage, the image may still contains noises: either false negatives (holes in the middle of the matter) or false positives (matter in the background) (Fig. 2c). The *imfill* function in Matlab is used to remove the false negatives. It detects and fills the holes characterized by background pixels that cannot be accessed from the boundary pixels of the image through the face connectivities (6-connected mode). The false positives are filtered using the opening morphological operation (*imopen* function in Matlab) with a structuring element based on a 50 µm-radius ball. The solid component corresponding to the cholesteatoma is then extracted using the *bwselect3* function of Matlab (Fig. 2d). Its volume can be simply estimated by counting the voxels and multiplying the result by the voxel element volume. The computation time for the segmentation is about 5 s for a volume of $171 \times 193 \times 768$ voxels using a 1.6 GHz Intel Core i5.

C. Vaporized volume of cholesteatoma

The vaporized volume can be calculated as the difference of volume in the images before and after the laser ablation. The experiments were conducted in the hours following the cholesteatoma removal. Positioning the sample under the fiber tip takes around 1 minute and the scanning time is 20 seconds so each iteration takes a few minutes. The time delay between the operation and the experiments should be kept as low as possible because time alters the optical properties of the cholesteatoma [2].

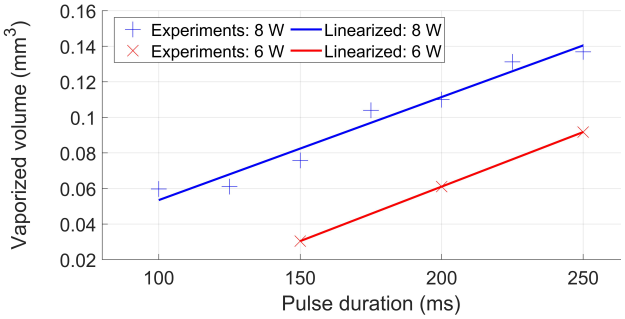


Fig. 3: Vaporized volume as a function of exposure time.

III. RESULTS

The experimental results of the vaporized volumes with respect to variant time exposures of the laser pulse for two different laser powers, 6 W and 8 W, are presented in Figure 3. In this experiment, the OCT can measure an ablation volume of 0.03 mm^3 (its resolution is even about 2.2×10^{-6} mm^3 for each voxel volume). One can confirm that the vaporized volume increases linearly with the exposure time. Moreover, the steady-state ablation rate increases when the laser power increases. This experimental result is consistent with the computational model in the literature [3]. As the tissue needs to be heated from its initial temperature (20 °C) to the water vaporization temperature (100 °C), there exists a minimum value of the pulse duration so that cholesteatoma can be vaporized with a given laser power. This limited value can be estimated using linear extrapolation from the vaporized volume - pulse duration line (e.g., 6 W and 105 ms).

IV. CONCLUSIONS AND DISCUSSION

This study provide an effective method for cholesteatoma laser ablation monitoring using OCT and the proposed image processing. Based on the obtained quantitative results, the surgeon can select the proper laser parameters (power and time exposure) as well as the required number of shots for any specific volume of residual cholesteatoma during the laser ablation process. More experiments can be conducted to obtain a complete description of the relationship between the cholesteatoma vaporized volume and the laser parameters.

As an ex-vivo study, there are probably several differences in the results comparing to the in-vivo practice such as: the presence of blood in the tissue, the higer temperature in human body (37 °C), or the tissue shrinkage due to natural evaporation of water in ex-vivo case. The best solutions to these limitations are making the experimental environment close to the middle ear condition and avoiding intraoperative bleeding.

Future work will focus on the integration of the OCT probe into our hybrid concentric tube robot [4] to perform cholesteatoma detection and laser ablation monitoring. The integrated OCT probe will also be used to control the distance between the fiber tip and the cholesteatoma during the ablation and study its impact on the ablation process.

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