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INVESTIGATING THE EFFECTIVENESS OF THREE-DIMENSIONAL-PRINTING FOR PRODUCING REALISTIC PHYSICAL SURGICAL TRAINING PHANTOMS

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Abstract: *Current simulation methods for surgical training present several restrictions in terms of accessibility, flexibility, costs and ethics. In this research, the potential of Three-Dimensional Printing (3DP) for the manufacturing of biological representative simulation materials for training phantoms has been investigated. The force experienced during surgical dissection of the human sinus has been quantified and used as a benchmark for the optimization of 3DP materials.*
The research has explored a wide range of properties achievable in 3DP through post-processing methods, which allowed the reproduction of force values in accordance with those registered with cadaveric human tissue.
Key words: *Three-Dimensional-Printing, Surgical Simulation, Sinus, Infiltration*

1. INTRODUCTION

Functional Endoscopic Sinus Surgery (FESS) is a relatively complex procedure involving the paranasal area. FESS consists, in part, in the resection and removal of tissue elements within the sinuses utilising endoscopic surgical instruments. The proximity of vulnerable structures, such as the carotid artery, optic nerve and brain, justifies an extensive high level of training for this operation. Surgical training represents an essential step to reduce the probability of human errors and negative consequences of treatment. Simulation is employed to enable training of scenarios and techniques. Several methods may be used, such as virtual reality (Pößneck et al. 2005), physical mannequins (Briner et al., 2007) and cadavers (Blaschko et al., 2007). However, when considered in isolation, each of methods present individual restrictions for their use. These range from these methods lack of accessibility and flexibility, to inadequately reproducing the properties of tissue, in particular during resection.

Rapid Prototyping (RP) technology, in particular Three-Dimensional-Printing (3DP), may present a promising alternative to allow the production of realistic simulation phantoms to be employed in FESS training. Feasible costs and the manufacturing speed are some of the main benefits. In addition, the porous nature of the green part produced by 3DP allows post-processing treatments, such as infiltration, which allows us to achieve a wide range of physical properties (Suwanprateeb 2008; Pilipovic et al. 2009). Some works have already evaluated RP for simulation model manufacturing (Schwager et al., 2003; Suzuky et al., 2004).

2. HUMAN SINUS CHARACTERIZATION

2.1 Materials and Methods

Depending on the location within sinus, the response perceived through the surgical instrument can vary considerably.

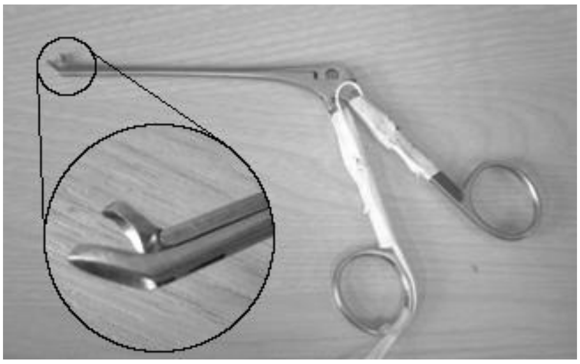

Fig. 1. Endoscopic surgical tool adopted in this work

The value of a physical phantom is related to the realistic feeling experienced during resection. This aspect requires a holistic description of the anatomical elements to be reproduced, in terms of structure and mechanical behaviour. A *discrete rongeur* was modified to measure the force experience during surgical resection (Fig. 1). Two strain gauges were mounted on each of the arms, and then coupled with a Wheatstone bridge. This translated the displacement occurring at the tool's arm in volt (V) variation. The output signal was acquired by a USB interface and recorded through a data logger software (12). Subsequently, the fracture force (N) was determined for each cut. The significant benefit of this method lies in the capacity to directly acquire and correlate the mechanical response from human sinus and prototyped samples.

A dissection test was conducted during a training course on ENT procedures, held at Copenhagen Hospital, using five fresh frozen cadavers. The resection on the cadavers was performed by a single expert surgeon. The test was restricted to three areas of the sinus: Bulla Ethmoidalis, Middle Turbinate and Medial Wall of Maxillary sinus. They were deemed representative of different resective characteristics in FESS.

Micro-CT images of a portion of the cadaveric sinus were adopted for the structural characterization of sinus structures. A classification of the existing tissues and their relative intensity's range was determined with aid of clinical expertise. A series of cross profiles (>10), oriented perpendicularly to the region of interest, were analysed for the following target regions: Bulla Ethmoidalis, Lamina Papyracea, Middle Turbinate, Maxillary Wall, Posterior Ethmoid, Uncinate Process and Superior Turbinate.

2.2 Results of Sinus Characterization

The dissection performed on five cadaveric samples returned the average fracture force for three selected areas; Bulla Ethmoidalis, Middle Turbinate and Medial Wall of Maxillary sinus, which presented values of 9.17N (±2.40N), 18.6N (±5.15N) and 21.37N (±5.89N) respectively. The micro-

CT illustrated the presence of different tissues within the sinus, such as bone and soft tissue (mainly mucosa).

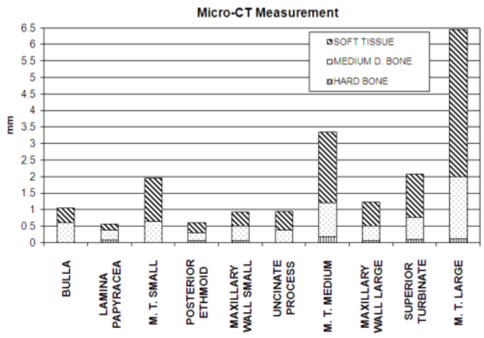

Fig. 2. Results of sinus tissue characterization

The Middle Turbinate and Superior Turbinate, presented a total dimension higher than the others, between 2mm and 6.5mm (Fig. 2). A major proportion of their thickness was soft tissue, which constituted between 67% and 69% of the total. Excluding the Turbinates, a large group of sinus elements ranged between 0.56mm and 1.23mm.

3. 3DP OF SINUS SIMULATION MATERIAL

3.1 Materials and Methods

The aim of this research was to evaluate a suitable combination of infiltrants for 3DP samples, which resembled the same fracture force values of human sinus tissue. A Z510™ Spectrum (ZCorporation®) was selected for the manufacturing of the samples. The target elements were produced with a thickness of 0.5mm and 1.00, in order to remain in the range of majority of sinus elements. The green parts were dried in an air-circulating oven at 80ºC for 1hour, and 120ºC for another hour. A series of different compounds were selected for the infiltration of the 3DP parts. They were Paraffin Wax (Paraplast X-TRA, McCormick Scientific), Acetate (Ronseal Ltd.), Polyurethane (Ronseal Ltd.), Epoxy Resin (Clear Coat™, System Three Resins Inc.), Silicone MM282 (ACC Silicones Ltd.) and Silicone AS1620 (ACC Silicones Ltd.). Epoxy Resin was diluted with Acetone before application. MM282 Silicone was thinned with a silicone fluid. The infiltrants were applied separately to the 3DP samples. Several combinations were proposed:

- #1: Polyurethane + Epoxy Resin (Dil. at 20%)
- #2: Acetate + Epoxy Resin (Dil. at 20%)
- #3: Acetate (x2) + Epoxy Resin (Dil. at20%)
- #4: Polyurethane + Epoxy Resin (Dil. at 15%) + AS1620
- #5: Acetate (x2) + Epoxy Resin (Dil. at 15%) + AS1620
- #6: Polyurethane + Epoxy Resin (Dil. at 15%) + MM282 (Thinned at 15%)
- #7 Acetate (x2) + Epoxy Resin (Dil. at 15%) + MM282 (Thinned at 15%)
- #8 Paraffin Wax + Epoxy Resin (Dil.15%) +MM282 (Dil.15%)
- #9: Paraffin Wax + Epoxy Resin (Dil.15%) + AS1620
- #10: Polyurethane + Epoxy Resin

A lapse of 48 hours was allowed between each application for full curing of the infiltrants. The same surgical tool adopted for dissection test on cadavers (Fig. 1), was adopted for the characterization of 3DP samples.

3.2 Results

The average of peaks force intensity was calculated and values were reported in Tab. 1.

Group	**Fracture Force [N] – 0.5mm**	***SD* [N]**	**Fracture Force [N] – 1.0mm**	***SD* [N]**
#1	26.14	*3.07*	28.04	*2.13*
#2	24.74	*3.15*	28.75	*2.26*
#3	23.89	*2.27*	28.35	*2.97*
#4	19.69	*2.83*	23.85	*1.5*
#5	22.66	*2.78*	30.96	*1.73*
#6	18.33	*2.89*	25.03	*3.09*
#7	23.51	*2.19*	30.7	*2.12*
#8	8.22	*1.4*	12.93	*3.02*
#9	9.52	*2.4*	14.16	*2.93*
#10	21.9	*2.11*	32.32	*2.82*

Tab. 1. Average fracture force of 3DP samples. SD Standard Deviation

The infiltrated samples presented fracture values in the order of those measured in the human cadaveric sinus. A qualitative assessment conducted by clinical experts confirmed the realistic behaviour and appearance of produced 3DP samples. For instance, group #2 and #3 behaved similar to Medial Wall. Group #5 presented the same feeling of Middle Turbinate. Groups #8 and #9 resembled weak sinus structures, such as Bulla Ethmoidalis.

4. CONCLUSION

This investigation highlighted a number of capabilities of 3DP for the manufacturing of representative materials for application in surgical training phantoms, although this RP technology is not optimal to resemble all relevant types of tissue, particularly soft tissue.

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