Inter-institutional protocol for the use of three-dimensional printing in the childhood epilepsy surgical planning:

from 3D modeling to neuronavigation

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Abstract - **This study is the first step in the effort for the use of three-dimensional (3D) printing in pediatric surgical planning by establishing effective collaboration between Ribeirao Preto Clinics Hospital (HCRP) and Renato Archer Center for Information Technology (CTI). The first printed biomodel can be used to support discussion and decision making, and neuronavigation before the surgery for training of cutting plans and incisions. The main focus of 3D printing for specific case handling is to reduce side damages by improving individual surgical planning and personnel training before surgery. One object representing brain and face segment of a patient was produced by 3D printing technology based on magnetic resonance imaging (MRI) data. Specific landmarks were measured by three distinct methods: manual caliper, InVesalius software measurement tool and neuronavigation coordinate detection. The mean coefficient of variation was 7.17% between all methods and landmarks measured. Our first results validate the combined use of biomodels with InVesalius software tools for assessment of individual brain anatomy providing manual handling and visualization of three-dimensional models. The creation of communication protocols between the teams involved and navigation protocols for quality control opens possibility of long term training program, congregating agents from research areas in Medical Physics, Medical Sciences and Neuroscience.**

Index Terms - additive manufacture, neuronavigation, surgical planning, open source software, InVesalius.

INTRODUCTION

The usefulness of visual resources to guide scientist in decision making process seems to be commonplace in the community. In the all day of surgical planning, specialists of different areas gather data available in the hospital image bank, process them and try to reach an a near to unanimous opinion about which approach to take during surgery. In this way, multimodal visual renderings encompassing anatomic locations, functional variations and structural relations must be at hand for a team to make decisions. As previously shown by a study with a multi-disciplinary team of scientists, the visual information is important not only for the manipulation of rendered data per se, but also to establishing a common ground for scientific understanding and production of evidence. When gestures, talk, gaze and other interactions come into place, there emerges a sense of embodiment that helps to transform the physical working space into a field of meaning production [1].

Some neurological conditions require reliable evidences and meaning for an acceptable decision on how and when to undergo surgery. In the case of refractory epilepsy, video-electroencephalography, tomography and resonance images are evidences of the side and areas responsible for epileptogenic activity [2]. Ressecting or disconnecting parts of the brain, in a way that the sane portions can work properly, may lead to desirable outcomes, including lower the seizure frequency and improved subjective quality of life [3].

Recent development of 3D printing technology has offered the opportunity of its use in a variety of domains, ranging from additive manufacture of buildings to nanoscale particle deposition. One of the most promising applications is the production of biomedical prostheses and mock-ups. Objects are rendered and printed to serve as a base for plaque modeling, cutting plane definition and creation of teeth-alveolar spatial relation retainers [4].

In the case of neurosurgery, the effective use of 3D printing technology in planning faces the challenge of establishing a protocol robust enough to avoid errors in the image-processing pipeline. It begins in the physician's office, thru effective printed object, until information about reliability in neuronavigation is available in the surgery room. Neuronavigation systems have contributed to achieving more accurate neurosurgery procedures with lower levels of incisions. The use of neuronavigation with 3D printed brain models extracted from tomographic images of patients allows surgeries planning based on the anatomical variations of each individual [5]. From all tomographic images, magnetic resonance imaging (MRI) offers good contrast in soft tissues and works in the safe radiofrequency range, providing necessary resolution for brain extraction with high spatial accuracy [6]. Yet, grayscale values may not be regular across the image, given the multi-coil nature of the acquisition and inhomogeneity of the biological tissue itself. Combining efforts to overcome the challenges to use 3D printing from MRI images for neurosurgical planning, this work establishes an inaugural protocol of collaboration

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between Medical School at Ribeirao Preto Clinics Hospital (FM-HCRP) and Center for Information Technology Renato Archer (CTI). The aim of this study is to establish a procedure for 3D printing of anatomical objects for childhood epilepsy surgical planning, using open-source neuronavigation software as a pivot for accessibility across knowledge-enhancing sites.

METHODS

One case, a 3-year old boy suffering from Sturge-Weber Syndrome, was elected as benchmark for processing pipeline. The protocol is under analysis for approval at the HCRP Ethical Committee. The volumetric T1-weighted images were submitted to SPM voxel-based morphometric segmentation with volumes matched to the MNI template, normalized and smoothed (8 mm FWHM). Compartments c1 (gray matter) and c2 (white matter) were averaged and thresholded for surface reconstruction in InVesalius open-source software [7]. The object representing the Sturge-Weber patient's head was printed by selective laser sintering technology. The object was composed by the brain surface, a sector around the head representing the face, temporal and occipital areas and four cylinders, which hold both surfaces in place (Figure 1). A communication protocol was developed to correctly trim the first virtual object (Figure 2).

The resulting printed object (Figure 3) was measured and used as a base for neuronavigation. Three modalities of linear measurements of anatomical landmarks were accomplished by two independent raters based on the 3DT1 MRI volume data of the patient. First, measurements were made in the 3D viewport of InVesalius software (Figure 4). Second, caliper measurements were done on the surfaces of the printed model. And finally, the same landmarks were measured during a neuronavigation session with a Polhemus Patriot (Polhemus, Colchester, USA) device (Figure 5). Two independent raters made measurements with a caliper and with the use of a 6 degrees-of-freedom 3D tracker stylus. In order assess the quality of the whole 3D object configuration, a cloud of points was recorded with the Polhemus stylus around the 3D printed skull to verify the quality of neuronavigation registration between the printed surface and the 3D volumetric image. Smaller anatomic traits were also marked to this aim.

This inaugural protocol is part of a long term plan of using 3D printing and neuronavigation as an aid in neurosurgical execution with the help of a robotic arm. Incremental procedures shall be implemented in order to establish a local human resources training program.

RESULTS

The protocol provided successful communication and data transfer between institutions. The printing of object was performed in the course of a week afforded by the ProMed project. The object offered a strong and vivid visual impression and its quality permitted the measurements of landmarks and the successful neuronavigation across the brain hemispheres.

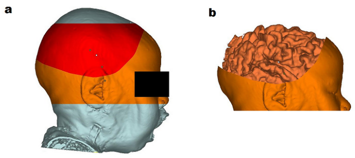

FIGURE 1
PROCESSING STEPS OF A VIRTUAL SOLID OBJECT AIMING AT THE TRIDIMENSIONAL PRINTING. A. CUTTING PLANES FOR THE SKULL SCAFFOLD DEFINITION (AXIAL PLANAR CUTS ON THE NOSE AND AT THE HEAD APEX, SUBTRACTING THE BLUEISH REGIONS, AND CURVED CUT FOR BRAIN EXPOSURE AND SUBTRACTION OF THE RED SURFACE). B. LATERAL VIEW OF THE MODEL TO BE PRINTED.

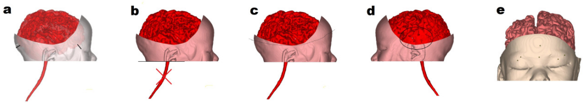

FIGURE 2
STEPWISE PROTOCOL TO PRUNE AND TRIM THE INITIAL MODEL PERFORMED BY HCRP AND CTI PERSONNEL. A. ORIGINAL VIRTUAL OBJECT RENDERED IN A TRANSPARENT SURFACE, EVIDENCING THE SUPPORTING CYLINDERS INSIDE (BLACK DASHES). B. MARK TO REMOVE A STRUCTURE FROM THE MODEL. C. MARK TO PARTIALLY SURFACE. D. SELECTION TO BRING ATTENTION TO A SEGMENTATION FAILURE. E. FRONTAL VIEW OF THE FINAL RESULT.

FIGURE 3
FINAL OBJECT PRINTED BY SELECTIVE LASER SINTERING.

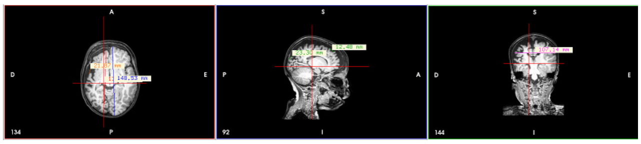

FIGURE 4
LINE SEGMENTS REPRESENTING THE DISTANCES TO BE MEASURED IN THE FINAL PRINTED OBJECT.

FIGURE 5
DEFINITION OF FIDUCIAL COORDINATES DURING THE NEURONAVIGATION SET-UP. LANDMARKS DEFINED IN FIGURE 4 WERE TRACKED AND MARKED WITH THE STYLUS AFTER POINT-BASED REGISTRATION.

Neuronavigation was satisfactory in the absence of ferromagnetic parts. Experimental setup inside a shielded room worked in a way that, after the registration step, the user could track his own movement with Polhemus stylus and the 3D cursor in real time. The degree to which one can trust that the printed model represents the actual patient´s anatomy could be measured by extensive and dynamical markings, covering the whole perimeter of the head or a certain anatomical accident (Figure 6a). In order to assess quality of the set composed by the biomodel, the resonance image and the stylus operator, a series of points lying along the post-central gyrus were recorded. Visual comparison of the resulting markers (Figure 6b) and the actual object (Figure 5) indicates that the segmentation processing obeyed the anatomic conformation of the patient's brain.

A developer version of the InVesalius software allowed customized parameter definition, being interesting for projects under development. Euclidean distances were calculated from saved raw coordinates. Greater distances of landmarks, e.g. anterior-posterior (AP) length of right hemisphere (RH), AP length of left hemisphere (LH) and lateral length of brain, presented a mean coefficient of variation of 1.43 ± 0.74%. Meanwhile, shorter distances, e.g. RH insula, RH cuneus and RH prefrontal, presented a mean coefficient of variation of 12.90 ± 7.35%. The mean coefficient of variation of all measurements was 7.16 ± 7.83%. The distance measurements for all methods are shown in Table 1. Tridimensional representation of landmarks is depicted in Figure 6c.

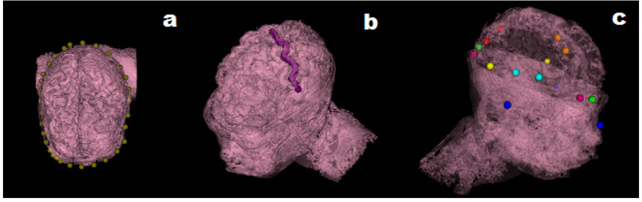

FIGURE 6

Neuronavigation results. a. Quality assessment of landmark definition during navigation. Axial view of points defining the trajectory of the stylus around the 3D printed skull (skin surface). b. Points defined along the postcentral gyrus, a common structured spared in brain resections. Quality of navigation registration is verified by visualizing the trajectory of points upon the reconstructed surface. c. Fiducial points (dark blue) and measurement points represented in the 3D viewport of InVesalius.

TABLE I

Linear distances (mm) calculated in the software viewport by one rater using a pachymeter and by two independent raters on the printed object.

Location	InVesalius	caliper	Rater 1	Rater2	C.V. (%)
AP RH	133.00	133.00	132.00	134.00	0.61
AP LH	148.53	152.00	147.5	148.9	1.63
rInsula	22.87	19.75	24.44	29.7	10.35
rCuneus	23.30	21.05	23.69	13.34	7.17
rPrefrontal	12.28	9.08	15.47	12.55	21.19
LR width	107.14	110.30	114.21	122.77	2.06

DISCUSSION

In general, the communication between the teams in the Hospital and in the Technology Center worked well, with little room for postponing or misunderstanding. Considering that the first personal contact between the teams was made in October, 2013 and the object was printed and delivered in January, 2014, one can say that both the teams and the official protocols (i.e. bureaucracy) are well adjusted to supply any demand.

No researcher which came into contact with the printed biomodel could avoid the "wow!" reaction. If virtual renderings may stimulate meaningful gestures and emerging interactions, the vision of a biologically plausible object affords the feeling of "this is everything I imagined and desired to have once in my hands". In fact, the possibility to grasp and rotate, inspecting every subtle corner of an actual anatomy can be really passionate for ones fond of Biology, Medicine, 3D Technology or, in this case, all at once.

As a work in progress, our procedure has some caveats that must be discussed. First, the measurements done here were executed by non-doctors, what may have introduced excessive variability in defining the landmarks. Also, the number of raters was small. A larger number of specialized raters would bring less variability with stronger confidence on the actual anatomical landmark.

CONCLUSION

The protocol proved to be robust for intact and resected brains, adequate for new patients and for those who need to reenter the surgery room. Neuronavigation made possible the measurement of distances between structures and to define trajectories that can be used for surgical planning.

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