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

From 3D modeling to neuronavigation

Carlo Rondinoni, Victor Hugo Oliveira e Souza, Renan Hiroshi Matsuda, André Cunha Peres Salles, Marcelo Volpon Santos, Oswaldo Baffa Filho, Antonio Carlos dos Santos, Hélio Rubens Machado
University of São Paulo
Ribeirão Preto, Brazil
hrmachad@usp.br

Pedro Yoshito Noritomi, Jorge Vicente Lopes da Silva
3D Technologies Lab
Center for Information Technology Renato Archer
Campinas, Brasil
jorge.silva@cti.gov.br

***Abstract*— This study is the first step in an effort to develop three-dimensional (3D) printing for use in pediatric surgical planning. In order to accomplish this, we established an effective collaboration between Ribeirao Preto Clinics Hospital (HCRP) and Renato Archer Center for Information Technology (CTI). Printed biomodels can be used to support discussions, decision-making, and neuronavigation before surgery. The main purpose of 3D printing for specific case handling is to reduce damage by enhancing knowledge of orientation during surgical planning and personnel training before surgery. Here, we produced an object that represented the brain and face segment of a patient via additive manufacturing technology based on magnetic resonance imaging (MRI) data. Specific landmarks were measured by three distinct methods: manual caliper, an InVesalius software measurement tool, and neuronavigation coordinate detection. The mean coefficient of variation was 7.17% between all methods and landmarks measured. Our results validate the combined use of biomodels with InVesalius software tools for the assessment of individual brain anatomy facilitating manual handling and visualization of 3D models. The establishment of communication protocols between the teams involved, as well as navigation protocols for quality control, presents the possibility of developing long term training programs, and promotes the congregation of individuals from research areas in Medical Physics, Medical Sciences, and Neuroscience.**

Keywords*— *additive manufacturing, neuronavigation, surgical planning, open source software, InVesalius

I. *Introduction*

The usefulness of visual resources to aid scientists in the decision making process seems to be commonplace in the community. In surgical planning, specialists of different areas compile data from the hospitals' imaging bank, process them, and try to reach a near-to-unanimous opinion regarding the approach that needs to be taken during surgery. In this way, multimodal visual renderings encompassing anatomical locations, functional variations, and structural relations must be available for a team to make decisions. As previously shown by a study with a multi-disciplinary team of scientists, visual information is important not only for the manipulation of rendered data, but also for the establishment of a common ground for scientific understanding and for the production of evidence. When gestures, speech, gazes, and other interactions come into place, a sense of embodiment emerges that helps to transform the physical working space into a meaningful field of production [1].

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

Recently developed three-dimensional (3D) printing technology can be used in a variety of domains, ranging from additive manufacture of buildings to nanoscale particle deposition. One of the most promising applications of this technology is in the production of biomedical prostheses and mock-ups. In instances such as these, objects are rendered and printed to serve as a base for plaque modeling, cutting plane definition, and for the creation of teeth-alveolar spatial relation retainers [4].

In the case of neurosurgery, the effective use of 3D printing faces challenges in establishing protocols robust enough to avoid errors in the image-processing pipeline and in allowing for the understanding of a patient's anatomical abnormalities [5]. The use of this technology begins in the physician's office where an effective printed object is imagined and sketched up. Thus, only after virtual 3D designing and printing, information about the reliability of neuronavigation will become available in the surgery room. Neuronavigation systems have contributed to improving the accuracy of neurosurgical procedures. The use of neuronavigation with 3D-printed brain models designed based on tomographic images of patients allows surgical planning based on an individual's anatomy [6,7]. 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 [8]. However, grayscale values may not be regular across the image, given the multi-coil nature of acquisition and inhomogeneity of the biological tissue itself. In a combined effort to overcome these challenges so that 3D printing can be achieved from MRI images for neurosurgical planning, we established an inaugural protocol of collaboration between the Medical School at Ribeirao Preto Clinics Hospital (FM-HCRP) and the Center for Information Technology Renato Archer (CTI). The aim of this study was to establish a procedure for 3D printing of anatomical objects for use in surgical planning for childhood epilepsy patients. Successful completion of this aim will help to close the gap in validating the impact of the use of 3D-printed biomodels.

II. Methods

A 3-year old boy suffering from Sturge-Weber Syndrome was elected as a benchmark for the processing pipeline. The protocol developed here is under current analysis for approval by the HCRP Ethical Committee. Volumetric T1-weighted images were submitted for statistical parametric mapping (SPM) voxel-based morphometric segmentation with volumes matched to the Montreal Neurological Institute (MNI) template, normalized, and smoothed (8 mm Full Width at Half Maximum - FWHM). Compartments c1 (gray matter) and c2 (white matter) were averaged and used as a threshold for surface reconstruction in the InVesalius open-source software [9]. The object meant to represent the patient's head was printed using selective laser sintering technology. This object composed of the brain surface, a sector around the head representing the face, temporal and occipital areas, and four cylinders, which held 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 3A) was measured and used as a base for neuronavigation. Three modalities of anatomical landmark linear measurements were accomplished by two independent raters based on the 3DT1 MRI volume of the patient. First, measurements were made in the 3D viewport of the InVesalius software. Second, caliper measurements were done on the surfaces of the printed model. Finally, the same landmarks were measured during a neuronavigation session with a Polhemus Patriot (Polhemus, Colchester, USA) device (Figure 3B). Two independent raters made measurements with a caliper and a six degrees-of-freedom 3D tracker stylus. In order to assess the quality of the entire 3D object, 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 anatomical traits were also marked to this aim.

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

III. Results

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

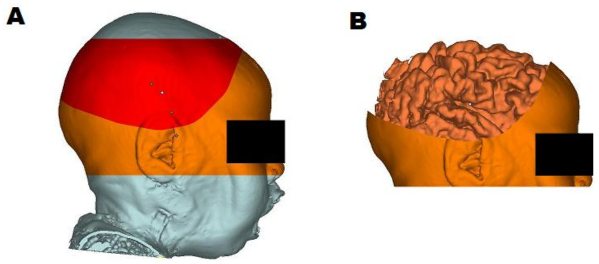

Fig. 1. Processing for 3D printing of a virtual solid object. A. Cutting planes for the skull scaffold definition (axial planar cuts on the nose and at the apex of the head, subtracting the bluish regions. Curved cut for brain exposure and subtraction of the red surface). B. lateral view of the model to be printed.

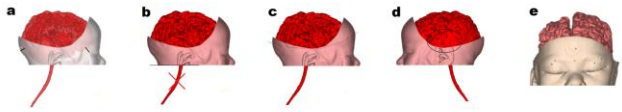

Fig. 2. Stepwise prototocol to prune and trim the initial model. A. Original vistual object rendered in a transparent surface, evidencing the supporting cylinders inside (black dashes). B. Mark to remove a whole surface from the model. C. Mark to partially remove a surface. D. Selection to bring attention to a segmentation failure. E. Frontal view of the final model.

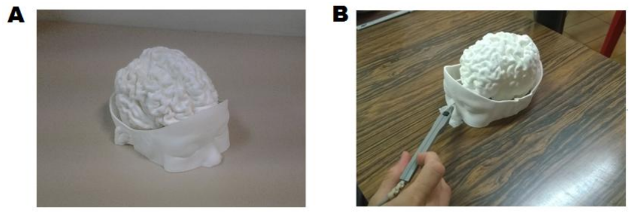

Fig. 3. A. Final object printed by selective laser sintering. B. Definition of fiducial coordinates during the neuronavigation set-up.

Neuronavigation was satisfactory in the absence of ferromagnetic parts. The experimental setup inside a shielded room worked in a way that, after the registration step, the user could track his own movement with a Polhemus stylus and a 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 4A). In order to assess the 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. A visual comparison of the resulting markers (Figure 4B) and the actual object (Figure 5) indicated that the segmentation process obeyed the anatomical conformation of the patient's brain.

A developer version of the InVesalius software allowed for the customization of parameter definitions, and this could be useful for future projects. Euclidean distances were calculated from saved raw coordinates. Greater distances of landmarks, e.g. anterior-posterior (AP) length of the right hemisphere (RH), AP length of the left hemisphere (LH), and lateral length of the 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. A tridimensional representation of all landmarks is depicted in Figure 4C.

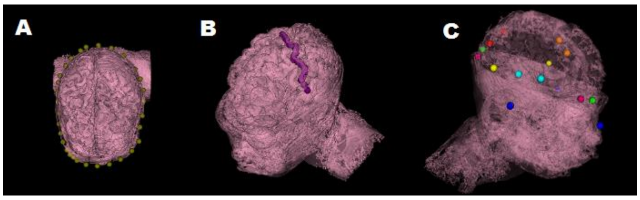

Fig. 4. Neuronavigation results. A. Quality assessment of landmark definitions. A. Axial view of points defining the trajectory of the stylus around the 3D-printed skull (skin surface). B. Points defined along the post-central gyrus. C. Fiducial (dark blue) and measurement points represented in InVesalius 3D viewport.

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***	***Rater 2***	***CV (%)***[a]
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

a. Coefficient of variation expressed as a percentage.

IV. Discussion

In general, communication between teams in the Hospital and in the Technology Center worked well, with little misunderstandings and few instances of having to postpone planning. 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 were well adjusted to supply the demand.

When the printed biomodel was shown to the researchers, they shared the impression that the richness of details regarding the represented anatomical complexity can afford useful interaction in the team. Thus, if virtual renderings on a computer screen can stimulate meaningful gestures and emerging interactions, the vision of a biologically plausible object affords the immediate possibility of surgical planning using a rendering of a patient's anatomy. Moreover, the potential to grasp and inspect details of the actual anatomy can enhance orientation during surgical procedures and can prove beneficial in patient outcome.

As a work in progress, our procedure has some caveats that should be addressed. First, the measurements done here were executed by non-doctors, and this may have introduced excessive variability in defining neuroanatomical landmarks. In addition, the number of raters was small; a larger number of specialized raters would result in stronger confidence of anatomical localizations.

V. Conclusion

The protocol proved to be robust for the production of a biomodel based on infant neuroanatomy. Neuronavigation made it possible to measure distances between structures and to define trajectories that could be used for surgical planning. Future models will include other modes of information (cortical functional maps and structural tractography), improving orientation and decision making and enhancing surgical outcome.

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