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**TITLE: Defining anatomical roadmaps for neurosurgery with mixed and augmented reality**

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For neurosurgeons it may be difficult to assess which anatomical structures are in close relationship once the cortex is transgressed. Thanks to augmented and mixed reality it is now possible to improve the ergonomic display of information (augmentation) and ‘see’ volumes of virtual models (mixed) projected in the depth of the white matter, therefore allowing the definition of roadmaps aiming to predefined landmarks for each stage to be used as guidance in an intraoperative context. Superimposing patient imaging-based models of vessels, ventricles, basal ganglia and fiber tracts during surgery may help neurosurgeons to assess navigation precision and keep an accurate orientation when proceeding through the white matter. In a recent publication in *JNS: Neurosurgical Focus* titled “Augmented reality–assisted roadmaps during periventricular brain surgery”, we defined surgical steps and predefined sets of landmarks to be used in Augmented-reality (AR) assisted neurosurgery<sup>1</sup>. This paper initiates the creation of an anatomical and neurosurgical research team to standardize neurosurgical approaches.

In this case series, the authors described from an educational perspective the use of AR to navigate periventricular important structures. Using sets of neurosurgical landmarks used at each step of an intervention, we have described standardized roadmaps. Approaching specific anatomical structures, the surgeon could optimize trajectories and decide which anatomical structures to use as landmark, to preserve and/or remove or sacrifice. Addition of other operative tools may help the surgeon to secure the extent of resection<sup>2</sup>.

In this paper we focused on lobar-based approaches. Nowadays lobar approaches could be considered as aggressive and non-selective approaches<sup>3</sup>. Nevertheless, neurosurgeons have relied on those types of approaches for decades. The basic principle of lobar-based approaches allow defining “sandbox” brain volumes considered safe and more minimally invasive surgeries should respect. Implementing these surgical principles using AR assisted approaches, could be helpful for younger physicians and may help to standardize the field worldwide. Interventions could be prepared and performed as a flight according to a flight plan with checks and standard operation procedures at each stage of the intervention<sup>4</sup>. Visualizing the anatomical structures precisely (bone landmarks, cisternal, ventricular, basal ganglia, vascular and fiber tracts) intraoperatively, may help to tailor neuropsychological paradigm during awake brain surgery or electrophysiological monitoring or mapping to assess boundaries functionally before proceeding further with surgery.

Virtual reality (VR), mixed reality (MR) and AR are tools which will transform healthcare during the coming decade. Issues will need to be addressed. Each technology comes with advantages and drawbacks. Patients will benefit from VR to be immersed in relaxing universes<sup>4</sup>, to reduce anxiety and pain<sup>5</sup>, and to promote rehabilitation. VR may be used to better assess complex cognitive functions during awake brain surgeries<sup>6,7</sup>, as well as learning anatomy<sup>8</sup> and training surgical procedures<sup>9</sup>. The projection of a virtual avatar using MR or surgical information using AR can be useful in surgery to refine the precision of the gesture, reduce morbidity and refine surgical planning<sup>1</sup>.

One major challenge for virtual, mixed and augmented reality technology is to control the user perception distinguishing virtual models from reality and preserving patients’ safety from errors, information overflow or inattentive blindness<sup>10</sup>. Development in the field being mostly driven by the video game and entertainment industry need to be tailored to comply with healthcare needs regarding safety, precision and reliability as well as personalized care,

data protection and costs. It will most probably be necessary to train surgeons before using MR or AR to perform interventions. Indeed, it would be illusory to believe that one can master the use of such advanced tools intuitively after a single try. It will be highly recommended to establish quickly worldwide standards in the MR/AR environment design, training programs and certifications allowing practitioners. In our opinion training in MR/AR should be heavily focused on improving the knowledge regarding anatomy and neuroanatomy using VR.

Standard training and certification should be coupled to a phase of mentoring allowing the physician to assess his skills without exposing patients to any risk. It is expected that MR/AR assisted surgery will open new opportunities performing surgeries currently considered as impossible but care will be needed to avoid overconfident exploratory expeditions. These tools will require training and it will be our duty as a community to make the best use of those technologies.

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