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Short Research Communication

QUANTIFICATION OF THE INTERVENTIONAL APPROACHES INTO THE PTERYGOPALATINE FOSSA BY SOLID ANGLES USING VIRTUAL REALITY

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ABSTRACT

Virtual reality is increasingly used in medicine for diagnostics, for visualisation of complex structures and for preoperative planning. In interventional radiology, minimally invasive approach could be described with a target point representing the desired needle tip position and an array of all possible trajectories leading to it resembling irregular “cone” or “pyramid”. We present a pilot study of planning a minimally invasive posterior infrazygomatic and suprazygomatic approaches into the pterygopalatine fossa using a solid angle as a measure of size of the approach in five virtually reconstructed heads. The minimally invasive approaches were planned by manually drawing the edges of “pyramids” that described each approach in 3D using virtual reality program Tracer. For each head, a transverse diameter was measured and for each approach a solid angle size, average edge length and estimated area on the skin from where the target point could be reached were calculated. We found that, the solid angle of posterior infrazygomatic approach was significantly larger than suprazygomatic approach (p<0.001). Furthermore, the transverse head diameter and solid angle in posterior infrazygomatic approach were negatively correlated (ρ=-0.55, p=0.0002), while transverse head diameter and the estimated area on the skin from where the target point could be reached in the suprazygomatic approach were positively correlated (ρ=0.37, p=0.0206). In conclusion, our findings provide important preliminary evidence on the feasibility of evaluating and comparing different minimally invasive approaches using virtual reality systems, and affirm the validity of solid angle as a measure of the size of the approach.

Keywords: Solid angle; virtual reality; interventional radiology; minimally invasive approach; procedure planning.

INTRODUCTION

The role of virtual reality has been increasingly recognised in surgical procedure planning where it can aid in the understanding of complex anatomical relationships, and its use has already been described for brain and abdominal tumour resections, nephrectomies, cerebral aneurysm clipping and others (Rizzetto et al., 2020). Moreover, it is also increasingly used for diagnosis since it allows “immersion” in the image to better visualize target areas and therefore improves detection, localization and evaluation of pathologic formations (Elsayed et al., 2020). In interventional radiology the use of virtual reality has been to date restricted mainly to visualization of complex structures before the procedure to improve operator confidence (Devcic et al., 2018) and for practicing interventional procedures using phantoms (Kuhlemann et al., 2017). Beyond the established clinical applications, virtual reality could be employed to study different percutaneous interventions, such as biopsies, ablations, and various infiltrations, and for exploring new potential approach techniques. 3D virtual probes are used for interactive measurement of various geometrical characteristics of organs (Janáček and Jirák, 2019). Virtual reality can be reconstructed from medical image data such as computed tomography (CT) volumes depicting bony structures, CT angiography volumes depicting bony structures and vessels, magnetic resonance imaging (MRI) volumes depicting soft tissue structures and co-registered CT with MRI that provide information on bony and soft tissue structures (Yoshinob et al., 2019; Elsayed et al., 2020).

Minimally invasive procedures are becoming increasingly important in modern medicine providing opportunity for targeted therapy which is a critical imperative for good treatment outcome (Sconfienza et al., 2020a, b; Snoj et al., 2020). In preparing for a procedure, it is of utmost importance to plan the optimal trajectory considering bony structures, vessels, and soft tissues such as nerves and glands. Target access is affected by the beforementioned structures, and this is even more pronounced where several structures conjointly affect the target access. This is the case in pterygopalatine fossa injections where several bony structures need to be accounted for to gain precise access into this narrow anatomical region on the skull base (Anugerah et al., 2020). The pterygopalatine fossa contains sympathetic and parasympathetic nerves, maxillary nerve and maxillary artery that supply nasal cavity, oral cavity and middle third of the face (Chiono et al., 2014). Injection of local anaesthetics into the pterygopalatine fossa is clinically used for treatment of specific headaches such as migraines, cluster headaches and post-dural-puncture headaches, for perioperative and postoperative pain management after maxillofacial and rhinologic procedures, and for management of posterior epistaxis (Chiono et al., 2014; Nagib et al., 2020).

A minimally invasive approach can usually be described by a target point describing the desired needle tip position and an array of all possible trajectories leading from the skin surface to the target point considering bony structures and soft tissue structures that should not be injured by the needle. Such array of all possible trajectories usually forms an irregular oblique “cone” or “pyramid” with the base at the surface of the skin, which can be described by several parameters such as area of the base, height, length of the axis, surface and volume. However, many of these parameters are grossly dependent on the size of the individual (e.g. if comparing two individuals with identical intrinsic anatomy and difference in size, the values of parameters describing the approach would be significantly different), and thus influenced by age, sex and race, making the comparison between individuals very difficult. On the other hand, the solid angle of the “cone’s” or “pyramid’s” apex is not dependent on the height of the “cone” or “pyramid” and could be appropriate parameter to describe and compare the sizes of minimally invasive approaches avoiding the influence of confounders such is the size of the individual. The aims of our pilot study were to examine the feasibility of virtual reality to study minimally invasive approaches into the pterygopalatine fossa and to study the appropriateness of solid angle as a measure of size of the approach.

MATERIAL AND METHODS

We studied the suprazygomatic and posterior infrazygomatic approaches into the pterygopalatine fossa bilaterally in five virtually reconstructed heads. The heads were reconstructed from CT volumes of five different patients that received CT scan at the University Medical Centre Ljubljana. All CT scans were performed on a Somatom Definition Flash (Siemens, Germany) CT scanner. Parameters of image acquisition and reconstruction were 120-kV tube voltage and 70/150 effective mA/s, pixel size 0.383 mm x 0.383 mm, pitch of 0.65, slice thickness of 0.75 mm and space between slices of 0.900 mm. The study protocols were reviewed and approved by Republic of Slovenia National Medical Ethics Committee (Permit No: 0120-538/2019/4).

The interventional approaches were described by “pyramids” with different numbers of sides. A target point, representing a needle tip in a clinical situation, was defined as a point in the pterygomaxillary fissure at the level of the pterygoid nerve channel and represented the apex of the “pyramid” for each studied approach. By manually drawing the lines (lateral edges of “pyramids”) from the target point to the point at surface of the skin considering bony structures, each approach was described by three-, four-, five- and six-sided “pyramid” so that the lines spawn the largest possible solid angle in every case (Fig. 1).

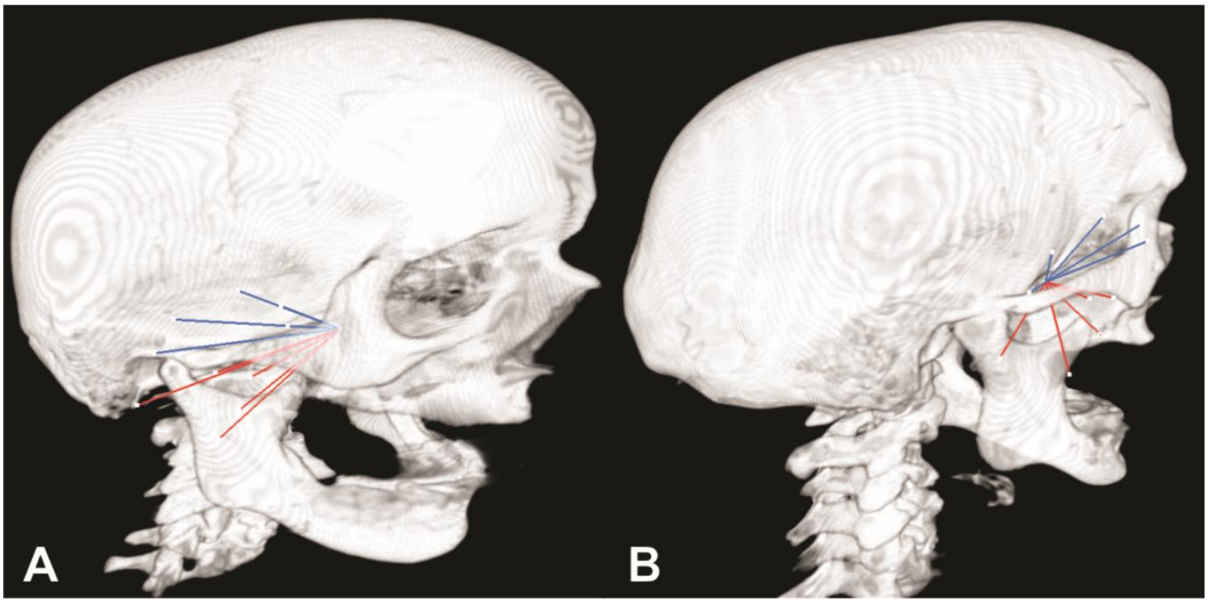

Fig. 1 *Lateral edges of five-sided "pyramids" representing the suprazygomatic (blue lines) and posterior infrazygomatic (red lines) approaches from the anterolateral (A) and posterolateral (B) perspectives. The tip of "pyramids" is located in pterygomaxillary fissure at the level of pterygoid nerve channel.*

We tested various sided "pyramids" to find the minimal number of sides that describes suprazygomatic and posterior infrazygomatic approach sufficiently. The lines were manually drawn in 3D using virtual reality program Tracer by Janáček et al. (2011). The program uses stereoscopic visualization with NVIDIA 3D Vision glasses (NVIDIA, California, USA), haptic feedback using Phantom Omni haptic device (3D Systems, South Carolina, USA) and space mouse (SpaceMouse® Pro, 3Dconnexion, Poland) (Fig. 2). The Tracer software returns coordinates of the points in space representing the apex and vertices of the" pyramids". The x and y coordinates of the apex and vertices were calibrated by pixel size, and z coordinates by the slice thickness.

Fig. 2. *The virtual reality setting with 3D Vision glasses, haptic feedback using haptic device and a space mouse.*

The solid angle at the apex is equal to the area Ω of spherical polygon with internal angles A_i that are equal to dihedral angles between neighboring lateral facets of the "pyramid". Area of the spherical polygon can be calculated using the Gauss-Bonnet formula:

$$\Omega = \sum_{i=1}^{N} A_i + (2 - N)\pi \quad (1)$$

Let V_0 be the apex and V_i the vertices on the head surface recorded in clockwise order, then the oriented lateral edges are

$$P_i = V_i - V_0 \quad (2)$$

and the normals to lateral facets are

$$Q_i = \frac{P_{i-1} \times P_i}{|P_{i-1} \times P_i|}. \quad (3)$$

Then the external angles B_i are

$$B_i = sign\, Q_i \times Q_{i+1}\, cos^{-1}\, Q_i \cdot Q_{i+1} \quad (4)$$

and the solid angle is

$$\Omega = \sum_{i=1}^{N} B_i + 2\pi \quad (5)$$

For each "pyramid" solid angle Ω and average length of the lateral edges were calculated:

$$\overline{P} = 1/N \sum_{i=1}^{N} |P_i| \quad (6)$$

The area (S) on the skin from where the target point could be reached was estimated using:

$$S = \Omega \times \overline{P}^2 \quad (7)$$

The size of the head was estimated by the transversal head diameter (D) measured as the distance between most lateral points of the mandibular condyles.

STATISTICAL ANALYSIS

Statistical analysis was performed using the GraphPad Prism 8 (GraphPad Software, San Diego, CA, USA). Shapiro–Wilk test was used to test the numerical data for normal distribution. The numeric parameters between two approaches, left and right side and different sided "pyramids" were compared with repeated measures ANOVA with Tukey's *post hoc* tests. The correlation between solid angle, length of lateral edges and area on the skin that represent the base of the "pyramid" was tested using Pearson's correlation coefficient. Data are represented as means and standard deviations. The differences were deemed statistically significant at $p<0.05$.

RESULTS

In the present pilot study, we studied suprazygomatic and posterior infrazygomatic pterygopalatine ganglion block approach in reconstructed heads of three male and two female adult patients bilaterally (n=10) with transversal head diameter (D) of 15.2 ± 1.1 cm, ranging from 14.1 to 16.8 cm.

The solid angle of the posterior infrazygomatic approach was significantly larger than suprazygomatic approach when measured using four- (p=0.0002), five- (p<0.0001), and six-sided (p<0.0001) "pyramids" (Table 1). In the suprazygomatic approach, there was a significant difference in solid angle size between three- and six-sided "pyramids" (p=0.0267). In the posterior infrazygomatic approach, the three-sided "pyramid" had significantly smaller solid angle than four- (p=0.0045), five- (p=0.0018) and six-sided (p=0.0024) "pyramids". There were no significant differences between any parameters between left and right side.

There was a significant positive correlation between transversal head diameter and average lateral edge length in the suprazygomatic approach (ρ=0.58, p<0.0001) and posterior infrazygomatic approach (ρ=0.53, p=0.0004). We also noted a significant negative correlation (ρ=-0.55, p=0.0002) between transverse head diameter and solid angle in the posterior infrazygomatic approach, while there was no significant correlation between transverse head diameter and solid angle in the suprazygomatic approach. Furthermore, there was a significant positive correlation between transverse head diameter and the estimated area on the skin from where the target point could be reached in the suprazygomatic approach (ρ=0.37, p=0.0206), while there was no significant correlation in the posterior infrazygomatic approach.

Table 1. *Solid angle (Ω), average lateral edge length ($\overline{P}$) and estimated area on the skin from where the target area could be reached (S) for three-, four-, five- and six-sided "pyramids" for suprazygomatic and posterior infrazygomatic approaches.*

	Suprazygomatic approach			Posterior infrazygomatic approach		
	Ω	$\overline{P}$ (cm)	S (cm^2)	Ω	$\overline{P}$ (cm)	S (cm^2)
3-sided	$0.098{\pm}0.039^{+}$	5.3±0.6	2.8±1.3	$0.089{\pm}0.035^{*,\#,+}$	7.0±1.5	$4.2{\pm}1.8^{*,\#,+}$
4-sided	$0.106{\pm}0.040^{\Psi}$	5.1±0.6	$2.9{\pm}1.2^{+}$	0.135±0.028	6.6±1.0	5.9±1.7
5-sided	$0.108{\pm}0.043^{\Psi}$	5.3±0.5	3.0±1.3	0.140±0.033	6.6±1.0	6.1±2.0
6-sided	$0.114{\pm}0.041^{\Psi}$	5.3±0.6	3.2±1.3	0.146±0.036	6.5±1.0	6.2±1.9

$^{*}p<0.05$ vs. 4-sided, $^{\#}p<0.05$ vs. 5-sided, $^{+}p<0.05$ vs. 6-sided "pyramid", $^{\Psi}p<0.05$ vs. solid angle of posterior infrazygomatic approach (repeated-measures ANOVA). Data are means ± standard deviations.

DISCUSSION

We demonstrated that virtual reality can be used to study minimally invasive approaches and that solid angle with the distance from the skin to the target area can be used as a measure to quantify the size of a minimally invasive approach, which allows the comparison between different approaches. Moreover, we showed that posterior infrazygomatic approach is larger than suprazygomatic approach into the pterygopalatine fossa.

The virtual reality has already been used for planning several surgical and interventional approaches in individual patients (Ong et al., 2018; Cao and Cerfolio, 2019; Ayoub and Pulijala, 2019; Ghaednia et al., 2021), however, its importance in studying different minimally invasive approaches systematically has not yet been commonly exploited (Deora et al., 2020). In the present pilot study, we showed the feasibility of virtual reality to systematically study two minimally invasive approaches into the pterygopalatine fossa. There are several advantages of virtual reality to study minimally invasive approaches. It can be easily reconstructed from CT or MRI volumes. Individual approach can be studied in many patients, with different morphometric characteristics. It allows the correlation of different morphometric characteristics with the size of the minimally invasive approach; and enables more accurate manual measurements of distances and angles of 3D structures. By reconstructing virtual reality from co-registered CT angiographic and MRI volumes, it is easier to take into consideration several important anatomic structures such as bones, vessels, nerves and other important structures, and to study how different structures affect the size and path of minimally invasive approach (Knez and Vrtovec, 2020; Deora et al., 2020; Elsayed et al., 2020). However, virtual reality also has some limitations, such as ergonomic limitations from prolonged use and relatively high costs for hardware and software adoption and use (Porcino et al., 2017; Sutherland et al., 2019).

We demonstrated that the minimally invasive approach can be represented by different-sided "pyramid" like objects with the apex at the target point and the base on the skin. Such representation of approach is very convenient, since it can be described by only a small number of points in 3D space, allowing calculation of different parameters describing these objects from the coordinates of these points (e.g. solid angle, lateral edge lengths, surface area of the base). The number of points and thus sidedness of "pyramids" that sufficiently describe a concrete minimally invasive approach should be preliminarily tested for every studied approach. We noted that minimal sided "pyramid" that sufficiently describes the suprazygomatic approach is three-sided, while the posterior infrazygomatic approach is sufficiently described by minimally four-sided "pyramid". Note that increasing the number of sides increases the solid angle as the "pyramid" better fits the shape of complex anatomical structures. However, the observed increase from the minimal sufficient number of sides is probably clinically insignificant.

There was a positive correlation between the average lateral edge length and transverse diameter of the head, reaffirming that body size and thus the distance from the skin to the target point could influence the parameters describing minimally invasive approach that are in relationship with the distance from the skin to the target point (e.g. area on the skin from where the target point could be reached and volume of the tissue through which the target point could be reached). This makes the latter parameters less useful for quantifying minimally invasive approach size, since the differences in body size which can be due to different age, sex, race and body weight could significantly affect their value. Solid angle on the other hand is not dependent on the distance from the skin to the target point but is dependent only on the intrinsic anatomic relationship of structures that limit the interventional approach. Note that the average distance from the skin to the target point is also important and should be reported in the studies because it determines the needle length that should be used.

The posterior infrazygomatic approach was significantly larger than suprazygomatic approach, however, this does not necessarily mean that posterior infrazygomatic approach is superior to suprazygomatic approach because in the present pilot study we did not take the course of maxillary artery into account and the number of included subjects was only five. In clinical setting it is very important to avoid puncture of the maxillary artery to prevent unnecessary complications (Anugerah et al., 2020), therefore, further studies using CT angiographic volumes to reconstruct virtual reality and determine the size of solid angles for each approach considering the course of maxillary artery are warranted.

CONCLUSION

We employed virtual reality methods to study the spatial geometrical characteristics of two clinically important minimally invasive approaches to the pterygopalatine fossa, using solid angle with the distance from the skin to the target area as a quantification index to compare the size of the different minimally invasive approaches. Our findings provide important preliminary evidence on the feasibility of evaluating and comparing different minimally invasive approaches using virtual reality systems, and affirm the validity of solid angle as a measure of the size of the approach.

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