Revisiting the rules for freehand ventriculostomy: a virtual reality analysis

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OBJECTIVE Frontal ventriculostomy is one of the most frequent and standardized procedures in neurosurgery. However, many first and subsequent punctures miss the target, and suboptimal placement or misplacement of the catheter is common. The authors therefore reexamined the landmarks and rules to determine the entry point and trajectory with the best hit rate (HtR).

METHODS The authors randomly selected CT scans from their institution’s DICOM pool that had been obtained in 50 patients with normal ventricular and skull anatomy and without ventricular puncture. Using a 5 × 5–cm frontal grid with 25 entry points referenced to the bregma, the authors examined trajectories 1) perpendicular to the skull, 2) toward classic facial landmarks in the coronal and sagittal planes, and 3) toward an idealized target in the middle of the ipsilateral anterior horn (ILAH). Three-dimensional virtual reality ventriculostomies were simulated for these entry points; trajectories and the HtRs were recorded, resulting in an investigation of 8000 different virtual procedures.

RESULTS The best HtR for the ILAH was 86% for an ideal trajectory, 84% for a landmark trajectory, and 83% for a 90° trajectory, but only at specific entry points. The highest HtRs were found for entry points 3 or 4 cm lateral to the midline, but only in combination with a trajectory toward the contralateral canthus; and 1 or 2 cm lateral to the midline, but only paired with a trajectory toward the nasion. The same “pairing” exists for entry points and trajectories in the sagittal plane. For perpendicular (90°) trajectories, the best entry points were at 3–5 cm lateral to the midline and 3 cm anterior to the bregma, or 4 cm lateral to the midline and 2 cm anterior to the bregma.

CONCLUSIONS Only a few entry points offer a chance of a greater than 80% rate of hitting the ILAH, and then only in combination with a specific trajectory. This “pairing” between entry point and trajectory was found both for landmark targeting and for perpendicular trajectories, with very limited variability. Surprisingly, the ipsilateral medial canthus, a commonly reported landmark, had low HtRs, and should not be recommended as a trajectory target.

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KEY WORDS external ventricular drainage; hydrocephalus; Kocher’s point; ventriculostomy; virtual reality; surgical technique
grid of frontal entry points and 1) 90° entry angles, 2) common landmark-based trajectories in the coronal and sagittal planes, and 3) the ideal angles for a ventricular puncture of the ipsilateral anterior horn (ILAH) for each entry point. The primary objective of our study was to search for the entry point and trajectory with the highest success rate and to compare this rate with the success rates using established landmarks and rules described in the literature.

Methods

Patient Data

We used 50 randomly selected anonymized CT scans from our institution’s DICOM database (1-mm thin cut, 512 × 512 matrix) that had been obtained in adult patients (mean age 49.6 ± 20.5 years). Fifty-six percent (n = 28) were male and 44% (n = 22) were female. As was the case for most existing studies of freehand techniques reported in the literature, we used data from patients with normal anatomy and had not had a ventricular puncture. We included only slightly deformed ventricles who had normal skull anatomy and had not had a ventricular puncture. We included a wide range of skull dimensions with biparietal diameters ranging from 132 to 153 mm (mean 143 mm, SD 5.7 mm), frontooccipital diameters ranging from 168 to 210 mm (mean 186 mm, SD 9.9 mm) and a cephalic index (biparietal diameter/frontooccipital diameter × 100) ranging from 70 to 88 (mean 78, SD 4.1). Patients with a hydrocephalic configuration (Evans ratio > 0.3) and/or a mass lesion with displacement of ventricles or midline shift were excluded. The data sets were imported into the planning software of a navigation system (iPlan 3.0, Brainlab) to perform the procedures in virtual reality. The study was approved by the local institutional ethics review board (Cantonal Ethic Commission [Kantonale Ethikkommission], Bern University Hospital, Bern, Switzerland).

Entry Points

To cover the variety of entry points described in the literature and to include a wider range of potential new trajectories, a grid of 5 coronal × 5 sagittal = 25 virtual entry points was defined. The bregma was used as a topographical landmark for orientation of the 5 × 5 grid. The coronal suture, which is often used as a landmark, and our grid overlap widely. We used the 90° metric grid with reference to the bregma as the more reproducible map, because the coronal suture runs slightly anterior in the lateral direction.

The most posterior points were defined 1 cm posterior to the bregma, and the most anterior points 3 cm anterior to the bregma. The most medial points were defined 1 cm laterally and the most lateral points 5 cm laterally from the midline. For identification of each virtual entry point, we used a code in Roman numerals for the coronal position and in Arabic numbers for the sagittal position (Fig. 1).

Trajectories and Hit Rates

For all entry sites defined by the 5 × 5 grid, we measured 1) the hit rate (HtR) of a 90° trajectory (i.e., perpendicular to the skull) (Fig. 2); 2) the HtR and average entry angles when using the classic landmarks of the skull such as directions toward the ipsilateral medial canthus (IMC), the nasion, and the contralateral medial canthus (CMC) for the coronal plane as well as the tragus, 1 cm anterior (T+1) and 2 cm anterior (T+2) to the tragus for the sagittal plane (Fig. 2); and 3) for each entry point and patient the ideal angles for a trajectory hitting the middle of the frontal horn (Fig. 2). We then calculated the HtR by reapplying the averaged ideal trajectory for every entry point in each patient.

Using 5 × 5 entry points, the left and right sides, and 50 patients, 2500 trajectories with 90° entry angles, 2500 ideal trajectories, and 3000 landmark trajectories were examined. The latter were composed of 5 coronal entry points with 3 sagittal trajectories, and 5 sagittal entry points and 3 coronal trajectories in 100 hemispheres. Thus, a total of 8000 trajectories were investigated.

Trajectory Planning

Trajectories to the anatomic landmarks were planned separately for the coronal and sagittal planes. For the coronal plane, we used trajectories directed toward the IMC, the nasion, and the CMC, with an optimal sagittal orientation (i.e., toward a target at the center of the anterior horn). For the sagittal plane, we used trajectories directed toward the tragus, a point 1 cm anterior to the tragus (T+1), and a point 2 cm anterior to the tragus (T+2), with an optimal coronal orientation (i.e., again a target in the middle of the anterior horn).
For the definition of the “ideal” trajectory, we set the target for each entry point at the center of the ILAH. The coronal and sagittal entry angle of the “ideal trajectory” was measured for each entry point for the 50 patients on both sides. For every entry point, we calculated the average entry angles of the 100 ideal trajectories per point. We then calculated the HtRs by reapplying the average of the “ideal” coronal and sagittal angles to the 100 individual virtual punctures per point.

The trajectory path was followed in the axial, coronal, and sagittal planes, and the structures touched by the trajectory were recorded. We separately assessed successful cannulations of the ILAH, the ipsilateral pars centralis (ILPC), the contralateral ventricle (CLV), and whether the catheter entered the ventricle.

Statistical Analysis
Hit rates are given as percentages. Mean entry angles ± standard deviation were calculated using Microsoft Excel 2016. To visualize the results, we color-coded the measurements and summarized them in a heat map created with Adobe Photoshop CS4 (Adobe Systems).

Results
Perpendicular Trajectories
Using perpendicular trajectories (i.e., at a 90° angle to the skull surface in the sagittal and coronal planes), we recorded HtRs for the ILAH ranging from 0% to 83%. The highest HtRs were found for coordinates 2–3 cm anterior to the bregma and 3–5 cm lateral to the midline (63%–83%). Trajectories located at the level of the bregma or behind it had the worst HtR, followed by those located 1 cm lateral to the midline (Fig. 3).

Trajectories to Anatomical Landmarks
Coronal Subtrajectory
For the coronal plane, the highest ILAH HtRs of 92%
and 86% were noted at entry points 1 cm and 2 cm lateral to the midline for targeting toward the nasion, respectively. An 85% and a 78% HtR were found at entry points 3 cm and 4 cm lateral to the midline for targeting the CMC, respectively (Fig. 4). Thus, the HtR of the different coronal entry points depends on the coronal target (IMC, nasion, and CMC), i.e., they are “paired” (I and II with nasion, and III and IV with CMC). Interestingly, the trajectories to the IMC hit the ILAH with a rate ranging from 0% for the entry point 5 cm lateral to the midline to 29% for the entry point 1 cm lateral to the midline.

Sagittal Subtrajectory
The highest ILAH HtRs were 91% and 85% for entry points 3 cm and 2 cm anterior to the bregma targeting the tragus, respectively, 90% and 89% for the entry points 2 cm and 1 cm anterior to the bregma targeting T+1, respectively, and 90% and 88% for entry points 1 cm anterior to the bregma and at the bregma targeting T+2, respectively (Fig. 5). Thus, the HtR of different sagittal entry points also depends on the angle of entry toward a sagittal target, i.e., they are also “paired” (3 and 2 with T, 2 and 1 with T+1, and 1 and 0 with T+2).

Landmark Trajectory HtRs
A landmark-directed trajectory is always a result of targeting both in the coronal and the sagittal planes. Thus, the HtRs are calculated by multiplying the best coronal by the best sagittal HtR, and the best combined HtRs were in the range of 70%–84%.

Optimal Trajectories
When placing the optimal trajectory from each entry point to an ideal position in the center of the ILAH, the mean entry angles in the sagittal plane ranged from 89° ± 4° for a point 3 cm anterior to the bregma to a maximum of 106° ± 4° for a point 1 cm posterior to the bregma. In the coronal plane, the mean entry angles ranged from 87° ± 4° for a point 5 cm lateral to the midline to 94° ± 2° for a point 1 cm lateral to the midline. The higher standard deviation indicates a higher variability at more lateral entry points.

Hit Rate of Averaged Optimal Trajectories
Using the average ideal angles of the optimal trajectories for each entry point, we found, as expected, the highest HtRs of all trajectories (86%). Because we calculated the averaged ideal trajectory for all entry points separately, the HtR was high for all these entry points (76%–86%), but not applicable to a freehand puncture for most entry points.

Discussion
Freehand Ventricular Puncture
Ventriculostomy is one of the most common procedures in neurosurgery. Because it is assumed to be relatively simple to perform, it is often the first procedure taught to neurosurgical residents.34 However, misplacement of the ventricular catheter is
common. It may lead to direct injury or hemorrhage, and both complications increase in proportion to the number of passes. One study noted a 6% risk for noninfectious complications, of which two-thirds were associated with malpositioned catheters. Direct injury may occur when catheters pass into the basal ganglia, capsula interna, fornix, thalamus, plexus chooroideus, and vessels such as the superior thalamostriate vein or the posterior medial choroidal arteries. There are also reports of misplacement into the brainstem, sylvian fissure, interpeduncular, or suprasellar cistern as well as into the basal cisterns (carotid-ophthalmic, chiasmatic, prepontine). A recent meta-analysis found that hemorrhages occurred in approximately 7% of cases, but 6.2% were not clinically relevant. In addition, a position behind the foramen of Monro is regarded suboptimal as it may lead to obstruction of the catheter by the choroid plexus. According to the literature, a suitable position of the catheter using the freehand technique is achieved only after an average of 1.4–2.4 passes. Classic Rules and Anatomical Landmarks

Entry Points

The first description by Kocher, from 1892 in German and from 1894 in English, quoted an entry point “...2.5–3 cm from the median line and 3 cm forward of the precentral fissure.” Today, several different entry points are called “Kocher’s point” and are used with different trajectories. Instructions on how to perform a ventriculostomy can be found in a variety of journal articles and textbooks. Although they follow common principles intended to minimize complications, such as injury to the superior sagittal sinus and bridging veins as well as to the motor cortex, it seems that almost all possible combinations of entry points and trajectories are noted in the literature.

The recommendations for entry points in the sagittal plane range from just anterior to the coronal suture or bregma; 3 cm anterior to the precentral sulcus; 1 cm, 1–2 cm; 10 cm, or 12–15 cm posterior to the nasion; or 10 cm above the supraorbital ridge. These recommendations overlap, as the bregma is located on average 13 cm (12.2–13.8 cm) behind the nasion, and the coronal suture runs anterior in the lateral direction. Thus, for an entry site located 3–4 cm lateral to the midline, a sagittal entry point 1 cm anterior to the midline, a sagittal entry point 2 cm anterior to the coronal suture correspond to an entry point about 10 cm instead of 11 cm posterior to the nasion. In summary, the entry points recommended in the literature vary from 1.5 cm to 4 cm lateral to the midline, and from 10 to 12.5 cm behind the nasion.

Trajectories

The most often-reported trajectories are either a perpendicular (90°) puncture or toward the IMC, or the CMC in the coronal plane. In the sagittal plane, the recommended trajectories are “down- and backward,” through the external acoustic meatus, 1 cm anterior to the tragus, or 1.5 cm anterior to the tragus.
It is not always easy to identify these landmarks reliably during surgery when sterile drapes are covering the patient. For a trajectory toward the nasion and tragus, it was found that 90% of the catheters reviewed were placed within a 30° cone around the foramen of Monro, indicating a high variability when using anatomical landmarks.

Interpretation of Study Results

Comparison of Methods

The best HtR for the ILAH using a 90° trajectory (83%) is comparable to the best HtR with a landmark trajectory (84%). Interestingly, the best HtR for an idealized trajectory is almost the same (86%). This indicates that there are entry points for which the trajectory of a 90° angle or a landmark target matches the idealized trajectory.

Lessons Learned

Surprisingly, the IMC, one of the most often used coronal targets for the trajectory, had rather low HtRs even when the most medial entry point was used (Fig. 4). This finding was also reported in another virtual reality study in which the HtR for trajectories from an entry point at the midpupillary line to the IMC was only 10%. These findings are corroborated by a simple geometrical analysis based on anatomical measurements: 1) The average position of the IMC is approximately 15 mm lateral to the midline (normal intercanthal distance of approximately 30–31 mm). 2) The average anterior horn width of the ventricle in nonhydrocephalic patients is approximately 17 mm (left and right total anterior horn width of 31–37 mm). 3) The lateral roof of the ventricle is situated about 60% of the distance from the entry point at the level of the skull to the IMC (Fig. 2C).

Using these anatomical relationships, a line connecting the IMC and the lateral border of the anterior horn of the ventricle meets the level of the skull around 20 mm lateral to the midline, indicating that the entry point should be medial to this line to hit the nonhydrocephalic ventricle. It also demonstrates that the likelihood of misplacement of the catheter into the basal ganglia and internal capsule is higher when using the IMC than when using the nasion or the CMC as the target for the trajectory.

Another lesson we learned was that the entry point and trajectory are strongly connected. Although a high HtR can be achieved at several entry points, and with several trajectories, they are not arbitrarily interchangeable. There are specific “pairings” of the coronal entry point with the coronal orientation of the trajectory as well as of the sagittal entry point and the sagittal orientation of the trajectory. A more lateral entry point requires a more medial orientation of the trajectory and vice versa, and a more posterior entry point requires a more anterior orientation of the trajectory and vice versa, to keep the center of rotation within the ILAH of the ventricle (Fig. 6). There are 2 pairings for the coronal plane trajectory: 1) entry points 1 or 2 cm lateral to the midline and nasion, and 2) entry points 3 or 4 cm from the midline and CMC. There are 3 pairings for the sagittal plane: 1) entry points 10 or 11 cm posterior to the nasion (bregma = 13 cm posterior the nasion) that are paired with the tragus; 2) entry points 11 and 12 cm posterior to the nasion and a target of T+1; and 3) entry points 12 and 13 cm posterior to the nasion, and a target of T+2. According to our study, using other “pairs” would lead to significantly lower HtRs. This pairing also holds true for the 90° trajectory. It is noteworthy that a perpendicular insertion of the catheter only leads to high HtRs in conjunction with specific entry points; otherwise, both in the coronal and the sagittal planes, the catheter may miss the ILAH or the entire ventricle (Fig. 3).

Recommendations

In addition to guiding practitioners to achieve high HtRs of the ideal target—the ILAH—recommendations should take into account other aspects, such as safety, tolerance, a backup landmark, total HtR (including the ILPC), and a guide for trajectory correction.

To avoid the sagittal sinus, lateral venous lacunae, and the basal ganglia, entry should only be made at locations 2–4 cm lateral to the midline. The most robust entry point and trajectory for the highest ILAH and total HtR would be 3–4 cm lateral to the midline and 2 cm anterior to the bregma, targeting the CMC, and 1 cm anterior to the tragus (3-2-1 rule). As a backup, a perpendicular (90°) insertion at the same entry point also provides high HtRs. For this point, both methods can be combined, although a reliable 90° trajectory without any assistive device is difficult to achieve.

Study Limitations

Landmark-based rules do not consider the individual patient’s anatomy. Therefore, they will never attain the...
very high success rates of 88%–100% achieved with sonography, neuronavigation, or CT guidance.11,18,20,25,28,29,48,51 Our cohort consisted exclusively of adult patients and we would be cautious about extending our results to children, because we conducted no tests on children's skulls.

Another weakness is that we did not extend the grid beyond the 5 × 5-cm range. We might have missed points with good HtRs outside our grid; however, this seems unlikely, given the vicinity of the motor region, midline, and caudate nucleus, which are the limits for more posterior, medial, and lateral directions. A more anterior position would be anterior to the hairline in many patients.

Our study was completely image based. We considered this approach to be the most practical, as prospective randomized studies comparing different entry points, trajectories, and techniques are unlikely to be performed. Some might consider that freehand procedures are outdated and may also raise the criticism that our approach is based on average rather than individual anatomy. We have explained, however, that freehand puncture without image guidance is still the most often used procedure worldwide.

Conclusions

Rules for ventriculostomy should be stricter than those commonly published in textbooks and journals. There is little variability in the trajectory for a given entry point to achieve the highest HtRs for the ILAH. Entry points 1 or 2 cm lateral to the midline had the highest HtRs only in combination with a trajectory toward the nasion, and 3 or 4 cm lateral to the midline only in combination with a trajectory toward the contralateral canthus. The same pairing exists for entry points and trajectories in the sagittal plane. Surprisingly, the IMC had the lowest HtRs, even when the most medial entry point was used.

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