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Magnetic resonance imaging analysis of human skull diploic venous anatomy

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ABSTRACT

Background: The skull diploic venous space (DVS) represents a potential route for cerebrospinal fluid (CSF) diversion and absorption in the treatment of hydrocephalus. The goal of this study was to carry out a detailed characterization of the drainage pattern of the DVS of the skull using high-resolution MRI, especially the diploic veins draining to the lacunae laterales (LLs) since the LLs constitute an important channel for the CSF to access the superior sagittal sinus and subsequently the systemic circulation. The objective was to identify those skull regions optimally suited for an intraosseous CSF diversion system.

Methods: High-resolution, T1-weighted MRI scans from 20 adult and 16 pediatric subjects were selected for analysis. Skulls were divided into four regions, that is, frontal, parietal, temporal, and occipital. On each scan, a trained observer counted all diploic veins in every skull region. Each diploic vein was also followed to determine its final drainage pathway (i.e., dural venous sinus, dural vein, LL, or indeterminate).

Results: In the adult age group, the frontal and occipital skull regions showed the highest number of diploic veins. However, the highest number of draining diploic veins connecting to the lacunae lateralis was found in the frontal and parietal skull region, just anterior and just posterior to the coronal suture. In the pediatric age group, the parietal skull region, just posterior to the coronal suture, showed the highest overall number of diploic veins and also the highest number of draining diploic veins connecting to the LL.

Conclusion: This study suggested that diploic venous density across the skull varies with age, with more parietal diploic veins in the pediatric age range, and more occipital and frontal diploic veins in adults. If the DVS is ultimately used for CSF diversion, our anatomical data point to optimal sites for the insertion of specially designed intraosseous infusion devices for the treatment of hydrocephalus. Likely the optimal sites for CSF diversion would be the parietal region just posterior to the coronal suture in children, and in adults, frontal and/or parietal just anterior or just posterior to the coronal suture.

Keywords: Cerebrospinal fluid diversion, Diploic venous space, Skull regions

INTRODUCTION

Hydrocephalus is one of the oldest and most common problems faced by neurosurgeons.[1] Cerebrospinal fluid (CSF) shunting remains the mainstay of all treatment strategies, yet CSF shunting procedures are fraught with many complications that may adversely affect quality of life.[6,11,12,14]

Our research group has studied CSF absorption into the venous system through the major cranial venous sinuses for over 20 years.[5] CSF absorption is complex and probably varies between species, but the arachnoid granulations and cranial venous sinuses are undoubtedly involved in an important way in humans.[3] If CSF is normally absorbed into the cerebral venous system through the arachnoid granulations in the region of the lacunae laterales (LLs), and if the LLs were connected to the skull diploic venous system (DVS), then there might be a way to access the cerebral venous system through the skull diploic veins. This might be a pathway for CSF to access the major cranial venous sinuses without having to directly cannulate them and risk thrombosis and/or occlusion.[2] Previous work in our laboratory has shown that the DVS of the human and animal skull does indeed provide a potential route for CSF to access the cerebral venous system.[8,13]

The diploic space of the skull is the space between the outer and inner tables of the skull and contains a rich venous vascular network that connects directly to the major dural venous sinuses.[16] Fox *et al.*[5] showed that, in human cadaveric material, CSF moves from the arachnoid granulations in the parasagittal area of the dura into complex CSF channels and cisterns in the region of the LL. The LLs then drain directly into the superior sagittal sinus (SSS). Johnston *et al.*[8] inserted a series of specially designed intraosseous infusion devices into the skull diploic space in human cadaveric skulls and demonstrated that there was an anatomical pathway from the skull DVS to the SSS. Pugh *et al.*[13] then used similar intraosseous infusion devices in an animal model to show that crystalloid fluids infused through the skull gained ready access to the major dural venous system. Later, Jivraj *et al.*[7] used MRI to visualize the DVS in human skulls in an attempt to quantitate and characterize the diploic veins for consideration of possible intraosseous CSF infusion.

This current study seeks to build on previous MRI localization work and determines potential intraosseous skull infusion sites for the diversion of CSF in the setting of hydrocephalus. Specifically, we analyzed and characterized the normal *in vivo* anatomy of the human DVS using MRI scans obtained in both adult and pediatric subjects.

MATERIALS AND METHODS

Ethical approval

The study was approved by the Health Research Ethics Board of the University of Alberta.

Selection of MRI scans for analysis

Preoperative MRI studies from a random series of neurosurgical patients destined for the intraoperative MRI suite between November 2012 and September 2015 were analyzed. A total of 36 MRI studies were selected based on the following criteria:

Inclusion criteria

The following criteria were included in the study:
- Intact skull (male or female)
- Age >2 years
- MRI study (1.5T or 3T; 1 mm slice thickness and contiguous) with and without contrast to include entire skull.

Exclusion criteria

The following criteria were included in the study:
- Any previous surgery involving the skull (including prior craniotomy)
- Any abnormality involving the cerebral venous sinuses or the skull, as reported on official radiology reports.

Pediatric patients were defined as those <18 years and >2 years at the time of MRI scanning. Adult patients were >18 years.

MRI analysis

All patients underwent diagnostic MR imaging performed with a 1.5 T or 3 T system (Siemens, Erlangen, Germany) and a phased-array head coil. Each study was performed immediately before and after the administration of 0.1 mmol/kg of gadolinium (Gadovist; Berlex Laboratories, Montville, NJ). The pulse sequence used in all analyzed scans – because it allowed for the best resolution of the diploic venous space (DVS) – was a T1-weighted TurboFLASH magnetization prepared rapid gradient echo sequence tfl3dl_ns (1000/3.93 [repetition time msec/echo time msec], 15 degree flip angle, 256×256 matrix, 230 mm field of view, 1.0 mm section thickness, and 0 mm gap).

Skulls were divided into four regions corresponding to the underlying lobes, that is, frontal, parietal, temporal, and occipital regions. The frontal skull region was defined as the region of the skull anterior to the coronal suture and superior to the sphenofrontal sutures. The parietal skull region was defined as the region of the skull posterior to the coronal suture and superior to the squamosal suture, as well as anterior/superior to the lambdoid sutures. The temporal skull region was defined as region of the skull inferior to the squamosal and sphenofrontal sutures and anterior to the occipitomastoid suture. The occipital skull region was defined as the region of the skull inferior to the lambdoid suture and posteromedial to the occipitomastoid suture. [Figure 1] illustrates the divided skull regions.

All imaging analysis was performed by two observers and the DVS was identified in each skull region, as shown in [Figure 2]. Next, each diploic vein was counted in every skull
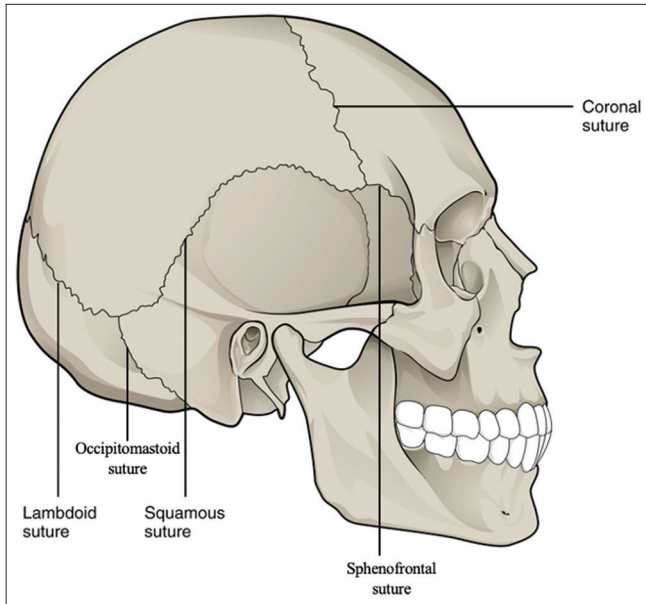
Figure 1: The definition of skull regions used in the data analysis based on the skull sutures. The frontal skull region was defined as the region of the skull anterior to the coronal suture and superior to the sphenofrontal sutures. The parietal skull region was defined as the region of the skull posterior to the coronal suture and superior to the squamosal suture and anterior/superior to the lambdoid sutures. The temporal skull region was defined as region of the skull inferior to the squamosal and sphenofrontal sutures and anterior to the occipitomastoid suture. The occipital skull region was defined as the region of the skull inferior to the lambdoid suture and posterior to the occipitomastoid suture. Source https://openstax.org/books/anatomy-andphysiology/pages/7-2-the-skull. licensed under the Creative Commons Attribution 3.0 Unported license;https://creativecommons.org/licenses/by/3.0/deed.en. Additional naming designation of the sutures was made.
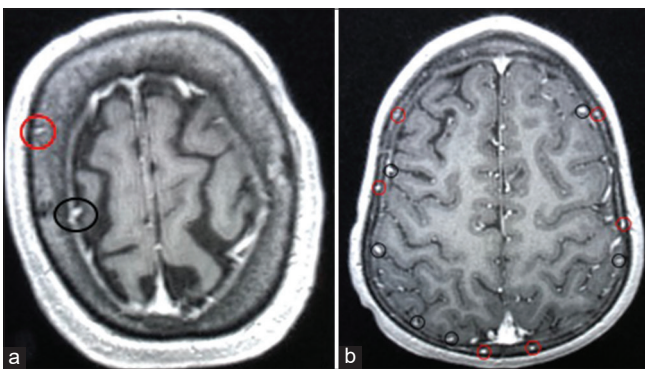

Figure 2: Illustration of the diploic veins versus cortical veins. The red circles in A and B are identifying the veins coursing in the diploic venous space. Each diploic vein was counted in each skull region and was followed to identify the ultimate pathway. Cortical veins were not counted but are encircled with black circles for illustration.

region and each diploic vein was followed to determine its course and final drainage pathway.

Drainage pathways were classified as follows:
- Draining into a dural venous sinus or dural vein
- Draining into the LL
- Indeterminate drainage.

[Figure 3] shows multiple continuous pictures to illustrate the methodology of diploic venous counting and the different pathways. 3D reconstruction of the identified veins and their pathways in diploic space was performed using special software created in our laboratory.

Statistical analysis

There was no difference in mean number of diploic veins between the right and the left right sides for each of the four skull regions (i.e., frontal, parietal, temporal, and occipital, $P > 0.05$ by paired t-test for all regions), so all subsequent comparisons between skull regions were done using summed right and left vein totals.

The mean number of veins was compared between skull regions using repeated measures analysis of variance with pairwise *post hoc* comparisons. $P < 0.05$ was considered statistically significant. Correction for multiple comparisons was carried out using Tukey's test.

All statistical analyses were carried out using Prism version 8 (GraphPad Software Inc.)

RESULTS

A total of 20 adults brain MRIs and 16 pediatrics brain MRIs were analyzed.

Adult diploic venous anatomy

[Figure 4] summarizes regional differences in diploic veins for adult subjects. The mean number of veins in the temporal region (5.2 ± 4.8) was significantly lower than in all three other regions ($P < 0.0001$ for all). The frontal and occipital regions had the most veins (24.0 ± 11.1 and 23.9 ± 11.6, respectively, $P = 1.0$), significantly higher than the parietal region (17.5 ± 7.8, $P < 0.05$ for both). When examining only diploic veins with clear evidence of drainage (i.e., excluding those with indeterminate drainage), once again the frontal and occipital regions had the most veins (11.6 ± 9.6 and 13.7 ± 9.5, respectively, $P = 0.7$), though not significantly different from the parietal region (9.2 ± 6.4, $P > 0.05$). The frontal, parietal, and occipital regions all had significantly more draining veins than the temporal region (4.3 ± 3.3, $P < 0.02$ for all). When examining only diploic veins draining into the LL, which occurred in 15/20 (75%) of subjects, we found that the bulk of these were in the frontal and parietal regions; in fact, there was only one example across all 20 adult subjects of a vein draining into the LL originating in either the temporal or occipital regions.
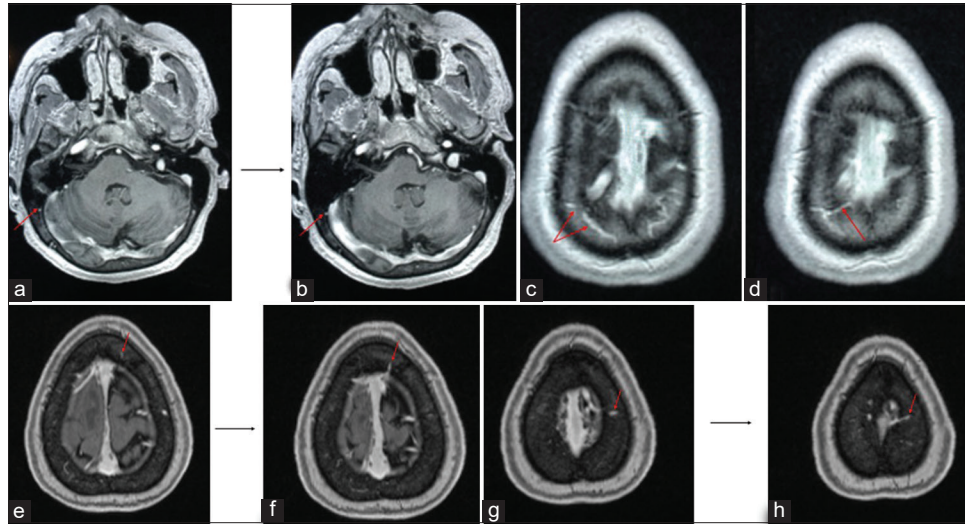
Figure 3: Illustrations of the different pathways for the diploic veins. The MRI in (a and b) shows a diploic vein in the right occipital region marked with red arrow appearing to drain directly into the transvers sinus. The MRI in (c and d) shows diploic veins marked with red arrow in the right parietal region which appear to drain into the lateral aspect of the superior sagittal sinus. The MRI in (e and f) shows a diploic vein in the left frontal region marked with red arrow appearing to drain into the superior sagittal sinus. The MRI in (g and h) shows a diploic vein in the left parietal region marked with red arrow appearing to drain into the lacunae laterales.
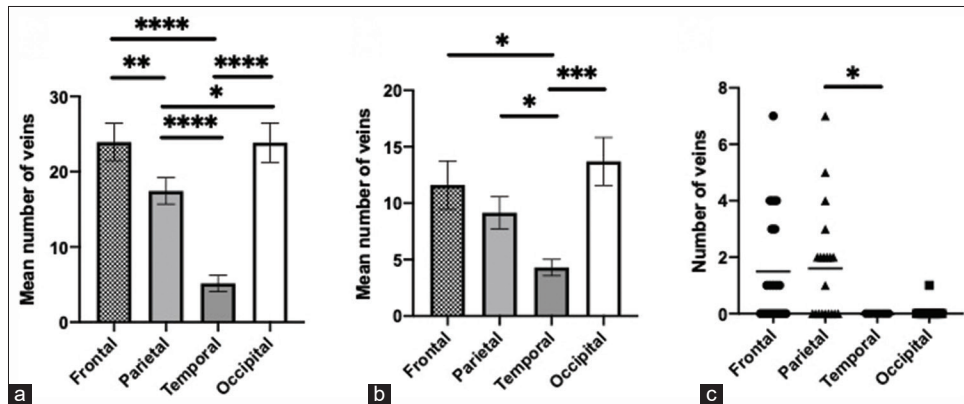

Figure 4: Adult age group findings. (a) The comparison and significant difference in the mean number of veins in the four skull regions, (b) the comparison and significant difference in the mean number of draining veins in the four skull regions, (c) the comparison and significant difference in the number of veins draining to the lacunae laterales in the four skull regions. * = p<0.05, ** = p<0.01, *** = p<0.001, **** = p<0.0001.

Pediatric diploic venous anatomy

[Figure 5] summarizes regional differences in diploic veins for pediatric subjects. As in adult subjects, the mean number of veins in the temporal region (0.6 ± 0.8) was significantly lower than in all three other regions ($P < 0.001$ for all). The parietal region showed a trend toward to having more veins (13.0 ± 4.9) on average than the frontal or occipital regions (8.9 ± 4.8 and 9.2 ± 6.1), but this did not survive correction for multiple comparisons. For diploic veins with clear evidence of drainage (i.e., excluding those with indeterminate drainage), there were similarly significantly fewer veins in the temporal region (0.4 ± 0.7) compared to the frontal (5.9 ± 4.7), parietal (9.3 ± 6.3), or occipital regions (7.6 ± 6.3), and once again, there was a trend to a greater number of

veins in the parietal region, but this did not reach statistical significance. When examining only diploic veins draining into the LL, which occurred in 15/16 (94%) of subjects, there were no such veins across all subjects in the temporal and occipital lobes. In the frontal region, 8/16 subjects (50%) had no veins draining to the LL, while in the parietal region, only one subject had no such veins. Overall, the mean number of veins draining to the LL in the parietal region was 6.7 ± 4.2, which was significantly higher than compared to any of the other regions ($P < 0.04$ for all).

DISCUSSION

Multiple studies have suggested that the DVS of the skull might serve as a potential absorptive site for CSF to return
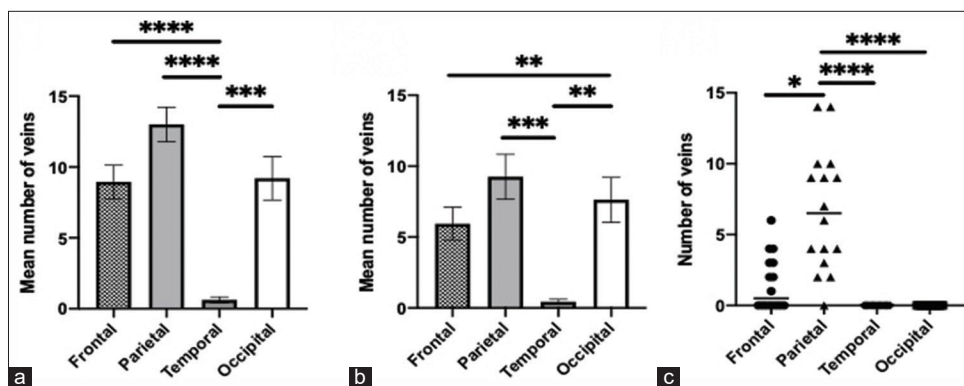
Figure 5: Pediatric age group findings. (a) The comparison and significant difference in the mean number of veins in the four skull regions, (b) the comparison and significant difference in the mean number of draining veins in the four skull regions, (c) the comparison and significant difference in the number of veins draining to the lacunae laterales in the four skull regions. * = p<0.05, ** = p<0.01, *** = p<0.001, **** = p<0.0001.

to the systemic venous system.[8,13] Our study attempted to determine whether or not there were more optimal regions of the skull to consider as potential access sites for access to these conduits for CSF drainage.

We found that while there was considerable variability in diploic venous anatomy between patients, there were certain patterns that emerged and differed somewhat between adult and pediatric subjects.

When dividing the skull into four regions, across all subjects, we found that the temporal region had the lowest number of diploic veins. In adults, the frontal and occipital regions contained the highest number of diploic veins, including draining diploic veins. Interestingly, in pediatric subjects, the parietal region had more diploic veins including draining veins. Overall, these findings suggest that the DVS in the skull undergoes developmental changes with aging. Further investigation is required to elucidate the developmental trajectory of changes in diploic vein concentration. We speculate that, in adults, the occipital region may exhibit a large number of diploic veins because the occipital bone is the thickest region of the skull.[10] However, it is unclear why the parietal bone has a higher number of diploic veins in younger subjects, given that the occipital bone is also consistently the thickest skull bone in the pediatric population as well.[9]

Another novel analysis we carried out is a detailed evaluation of diploic veins which drain to the LL. The LLs constitute an important channel for the CSF to access the SSS and subsequently the systemic circulation.[5] Fox *et al.*[5] using scanning electron microscopy showed that the LLs play an important role in permitting the passage of CSF from the arachnoid granulations to the SSS. Consequently, we analyzed all diploic veins that drain directly to the LL. In adults, we found the frontal and parietal regions near the coronal suture to have the highest number of such diploic veins draining into the LL, whereas in pediatric subjects, the parietal region just posterior to the coronal suture contained the highest number

of such veins. This radiological finding is consistent with the anatomic location of the LL seen in cadaveric dissections, [Figure 6]. Taken together, our data on diploic venous drainage in general, and our specific data on drainage to the LL, suggest that the optimal site for an intraosseous CSF drainage system would be the parietal region just posterior to the coronal suture in children and the posterior frontal or anterior parietal region in adults just anterior or posterior to the coronal suture.

It is worth mentioning that multiple recent studies have suggested that the DVS contributes to CSF drainage.[17,18] Tsutsumi *et al.*[18] found that arachnoid protrusions (APs) drain CSF to the DVS and they classified these AP into three morphological types: tubular, vesicular, and extensive. They found the highest concentration of AP in the parasagittal region, consistent with the findings of Fox *et al.*[5] in 1996. Tsutsumi *et al.*[16] investigated the DVS *in vivo* (MRI) in 80 patients and 3 cadaveric heads. Their anatomical study found consistent diploic venous routes for each skull region draining either to the extracranial or intracranial venous system[16] and came up with a general anatomical (nonquantitative) description of the DVS. Tsutsumi *et al.*[17] in another study found CSF biomarkers to be significantly higher in diploic venous blood compared to peripheral blood which further emphasizes that the DVS is involved in CSF drainage. When they compared different skull regions, they found the occipital region to have the highest concentration of CSF biomarkers which may be explained by the high concentration of the diploic veins in the occipital region as our study found. They also found an age variability in the concentration of CSF biomarkers; our study also suggested age variability in terms of diploic venous density with more parietal diploic veins in the pediatric age range and more occipital and frontal diploic veins in the adult group. Toriumi *et al.* also showed an age-dependent developmental profile of the DVS in mice.[15] Tsutsumi *et al.* recently published an interesting anatomical study of the diploic veins of the cranial
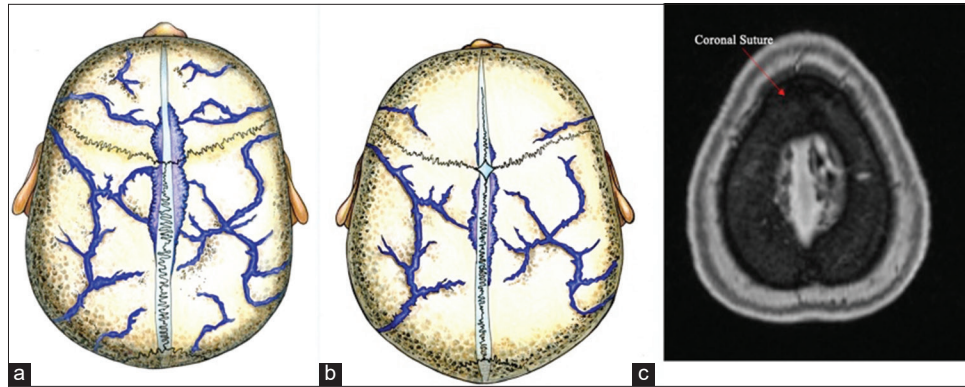
Figure 6: The Lacuane Laterales in relation to the coronal suture and skull diploic veins. The illustrative pictures in A and B shows the anatomic location of the LL just adjacent to the coronal suture which corresponds with the radiological finding of the highest number of diploic veins draining to the LL just anterior and just posterior to the coronal suture, in the adult age group and the pediatric age group, respectively. Please refer to Rhoton Cranial Anatomy and Surgical Approaches text book figure 4.14 a page 179 and figure 4.3 c page 164 for cadaveric dissection showing LL in relation to coronal suture. (a) Illustration showing the LL in relation to the coronal suture in adults. (b) Illustration showing the LL in relation to the coronal suture in pediatrics. (c) MRI MP RAGE showing the LL in relation to the coronal suture "red arrow pointing at the coronal suture."

base.[19] There are definitely diploic venous structures in the cranial base and the cranial vault and their interconnection and interaction could be the topic of further studies.

Bulleid *et al.* published an important case report regarding the absorption capacity of CSF by the DVS.[4] They reported a 9-year-old boy with Chiari malformation who underwent decompression but then began to experience low-pressure headaches in the postoperative period. He was found to have a CSF pseudomeningocele that had extended into the diploic space of the occipital bone at the site of the previous surgery. It was thought that the diploic space was possibly working as an absorptive site for CSF causing low-pressure headaches. He then underwent surgical reexploration and the diploic space was sealed with bone wax, which then relieved the low-pressure headaches. This case report suggested strongly that the skull diploic space had the capacity for CSF absorption.

Ultimately, while our anatomical study of diploic venous anatomy contributes important information in the quest to develop an alternate route for CSF absorption, our study was limited by a small and somewhat selected sample. Our methodology could be improved by fully randomizing our patient selection and including volunteers from the general population.

CONCLUSION

Previous work in our laboratory has suggested that the DVS might provide a route for CSF diversion. The current anatomical MRI study suggests some potential sites for the insertion of specially designed intraosseous skull infusion devices which can take advantage of the DVS, though much work remains before such devices become clinically viable.

Declaration of patient consent

Patient's consent not required as patients identity is not disclosed or compromised.

Conflicts of interest

There are no conflicts of interest.

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