Review

Superior cortical venous anatomy for endovascular device implantation: a systematic review

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ABSTRACT
Endovascular electrode arrays provide a minimally invasive approach to access intracranial structures for neural recording and stimulation. These arrays are currently used as brain–computer interfaces (BCIs) and are deployed within the superior sagittal sinus (SSS), although cortical vein implantation could improve the quality and quantity of recorded signals. However, the anatomy of the superior cortical veins is heterogenous and poorly characterised. MEDLINE and Embase databases were systematically searched from inception to December 15, 2023 for studies describing the anatomy of the superior cortical veins. A total of 28 studies were included: 19 cross-sectional imaging studies, six cadaveric studies, one intraoperative anatomical study and one review. There was substantial variability in cortical vein diameter, length, confluence angle, and location relative to the underlying cortex. The mean number of SSS branches ranged from 11 to 45. The vein of Trolard was most often reported as the largest superior cortical vein, with a mean diameter ranging from 2.1 mm to 3.3 mm. The mean vein of Trolard was identified posterior to the central sulcus. One study found a significant age-related variability in cortical vein diameter and another identified myoendothelial sphincters at the base of the cortical veins. Cortical vein anatomical data are limited and inconsistent. The vein of Trolard is the largest tributary vein of the SSS; however, its relation to the underlying cortex is variable. Variability in cortical vein anatomy may necessitate individualized pre-procedural planning of training and neural decoding in endovascular BCI. Future focus on the relation to the underlying cortex, sulcal vessels, and vessel wall anatomy is required.

INTRODUCTION
Neurointervention has grown rapidly in recent decades, mirroring the advancements in interventional cardiology observed in the mid to late 20th century.[1,2] This growth has been driven by the development of minimally invasive interventions for vascular pathologies such as stroke and cerebral aneurysm.[1] Despite these advances, there is a notable absence of endovascular electrophysiological interventions to treat neurological disease. In cardiology, the parallel development of permanent transvenous pacing, cardiac ablation, and cardiac mapping transformed patient outcomes using cardiac electronic devices.[3] Similar breakthrough devices are beginning to emerge in neurointervention, including stent electrode arrays and microscale robotic devices.

An early application of neurovascular electronic devices is brain–computer interfaces (BCIs). BCI devices serve as a bypass for neurological lesions between the cerebral cortex and the musculature,[4] facilitating prosthetic limb control,[5] speech restoration,[6] and the control of digital devices.[7] While intracranial BCI devices typically require burr hole craniotomy, endovascular BCI[7] is a novel approach which is both scalable[8] and minimally invasive.

The preferred target for endovascular BCI is the superior venous system, comprising the superior sagittal sinus (SSS) and its tributary veins (figure 1). This is due to the proximity of these vessels to primary and secondary sensorimotor cortices,[9] providing the opportunity for both high-fidelity decoding of motor intent[10] and the delivery of sensory feedback.[11] While current devices are deployed in the SSS,[7] the smaller cortical vessels of the superior venous system are subdural and in closer association with the cortex.[12] Targeting the cortical vessels therefore presents both an opportunity to improve signal-to-noise ratio and to increase the number of useful implants per individual.

In contrast to the venous sinuses, the numerous superior cortical veins are highly heterogenous and poorly characterized.[13,14] Notable superior cortical vessels include the vein of Trolard (superior anastomotic vein) and the Rolandic vein (central sulcal vein), along with many vessels draining the pial surface and bridging the subdural space to join the SSS. Attempts to characterize superior venous anatomy have historically been made to aid neurosurgical planning, primarily in cases of parasagittal meningioma.[15] These investigations have used imaging studies[16] and cadaveric microsurgical studies,[14] although samples have been small and no study has collectively reviewed the findings. Importantly, no study has considered these vessels in the context of endovascular device implantation.

In addition to a growing interest in cerebral venous disorders,[17] the emergence of endovascular BCI[18] has generated a pressing clinical need to develop a detailed understanding of this anatomy. This understanding requires a novel emphasis on vessel confluence angles, diameter, wall mechanics, and relationship to underlying cortex. All these features have implications for device design, preoperative planning, and subsequent decoding of neural signals. The importance of an improved understanding of vascular anatomy has a

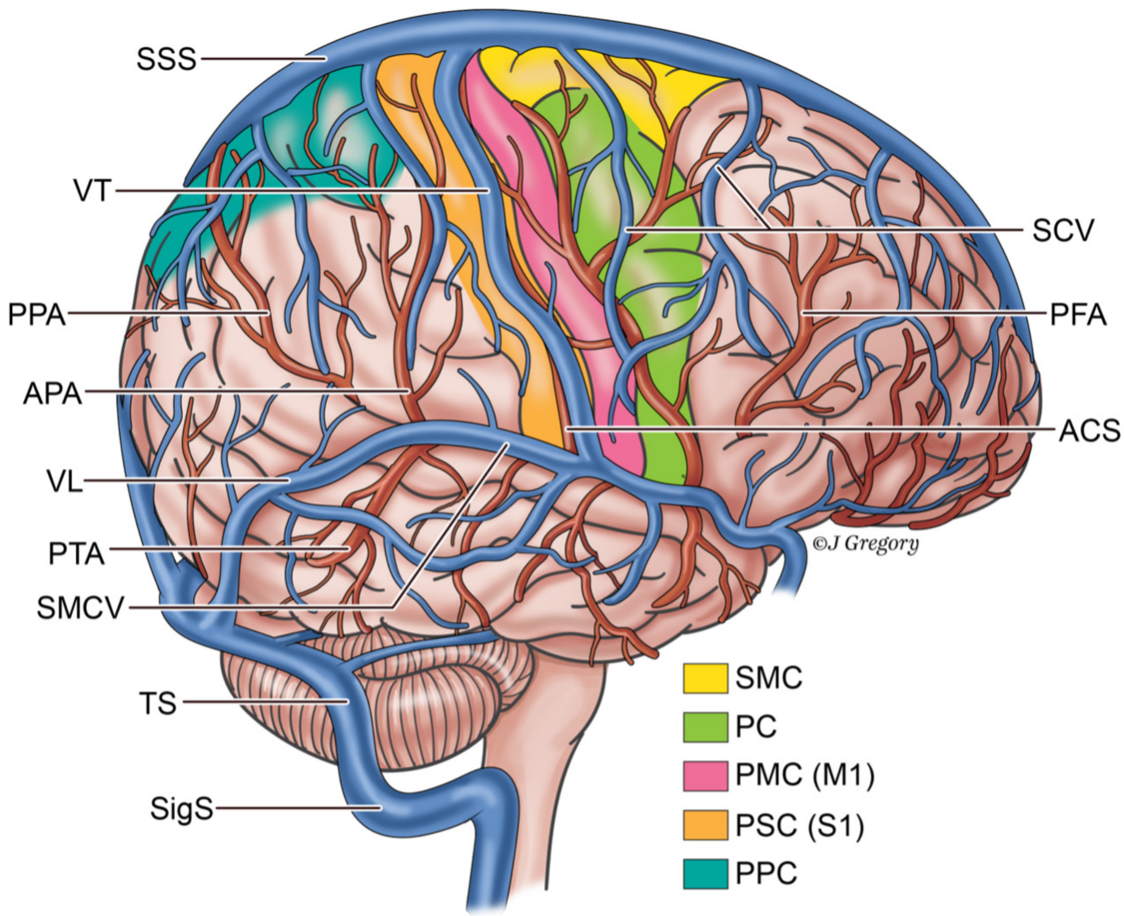

Figure 1 Illustration of cortical arteries and veins and proximity to regions of interest. Vessels flowing into the dural venous sinuses are not surrounded by dura. ACS, artery of the central sulcus; APA, anterior parietal artery; PC, premotor cortex; PFA, prefrontal artery; PMC, primary motor cortex; PPA, posterior parietal artery; PPC, posterior parietal cortex; PSC, primary sensory cortex; PTA, posterior temporal artery; SCV, superior cerebral veins; SigS, sigmoid sinus; SMC, supplementary motor cortex; SMCV, superficial middle cerebral vein; SSS, superior sagittal sinus; TS, transverse sinus; VL, vein of Labbé (inferior anastomotic vein); VT, vein of Trolard (superior anastomotic vein). Used with permission from © Jill K Gregory, CMI.

historical precedent in cardiology, where better characterization of the coronary venous system was developed to support pre-procedural planning in cases such as left ventricular pacing and ablation therapy.[19]

The aim of this systematic review is to provide a comprehensive characterization of superior cortical venous anatomy and to discuss this in relation to prospects for endovascular device implantation.

METHODS

A systematic review of the literature was performed, compliant with the preferred reporting items of systematic reviews and meta-analysis (PRISMA) guidelines (online supplemental material 1). The review was ineligible for registration with PROSPERO due to the absence of a defined clinical outcome.

Search strategy

Scoping searches were performed to assess existing literature and refine the review question. Final search strategies (online supplemental material 2) were developed for three databases (MEDLINE, Embase, and CINAHL) using an iterative process. To maximize sensitivity, no automated search limits or restrictions were applied. Searches were performed using Ovid (Ovid Technologies, New York, USA) and EBSCOhost (EBSCO Information Services, Massachusetts, USA) from inception to December 15, 2023. A medical librarian (IK) at the University of Cambridge reviewed and provided comments on the searches, which were incorporated into the final strategies.

Eligibility criteria

Screening for eligibility was performed in accordance with the following criteria:

Inclusion criteria

- Human study
- English language
- Superior cortical cerebral veins (small superior cortical veins, superior anastomotic vein/vein of Trolard, Rolandic vein)
- Any description of venous anatomy (position, diameter, angle, features)

Exclusion criteria

- Non-human
- Pathology likely affecting cortical venous anatomy (eg, arteriovenous malformation, cortical vein thrombosis)
- Letter

- Editorial
- Opinion article
- Conference abstract
- Full text not available

Selection process

Title and abstract screening were completed using Rayyan (Rayyan Systems Inc, Cambridge, USA). Two medically trained reviewers (JB and AM) performed screening. An initial blinded pilot screen of 50 records was completed to ensure concordance in application of inclusion and exclusion criteria. Decisions were unblinded with discussion between reviewers before proceeding. Both reviewers worked independently and were blinded to each other's decisions until screening was complete. For the purpose of this study, the term 'cortical vein' was defined to include any vessel draining into a cerebral venous sinus including anastomotic vessels and vessels situated on the surface of the pia mater which bridge the subdural space.

Data extraction, critical appraisal, and data synthesis

Articles were retrieved for full-text screening and data extraction using a piloted table. This was completed in duplicate by JB and AM. Any differences were reconciled through discussion and consensus. Quality assessment and analysis of risk of bias of all selected full-text articles were performed using the Anatomical Quality Assurance (AQUA) tool from the International Evidence-Based Anatomy (iEBA) working group.[20]

Due to the study heterogeneity and limited anatomical data, a meta-analysis was not possible. A qualitative synthesis was therefore conducted.

Data availability

The complete data extraction form can be found in the supplementary materials (online supplemental material 3).

RESULTS

Study selection

A total of 2320 records were identified from database searching. After removing duplicates, the initial search identified 1406 articles. Subsequent abstract and title screening eliminated 1307 articles, leaving 99 shortlisted for full text review. Of these, 24 were included in this study and four additional articles were identified by citation searching that met the inclusion criteria (figure 2).

Study characteristics

A total of 27 primary studies and one secondary study were included. All primary studies were observational in nature. In the primary clinical studies, the mean patient age ranged from 27 to 74 years and publication years were between 1989 and 2023.

The majority (19/27) of the included primary studies involved cross-sectional imaging. The remaining studies were either cadaveric (6/27) or intraoperative (1/27). One study comprised more than one form of analysis.

Only 19 (70.3%) primary studies reported quantitative anatomical data as specified by column headings in the piloted data extraction table. An evidence summary table of primary studies reporting anatomical data is shown in table 1. The summary table for the remaining studies can be found in online supplemental material 3. Anatomical data relating to the vein of Trolard (superior anastomotic vein) was most commonly reported. The most often reported feature was occurrence of the vein of Trolard.

Risk of bias

A risk of bias assessment is reported for all included studies (online supplemental material 4). In summary, imaging methods were poorly reported and it was sometimes not clear if a second investigator repeated vessel measurements. When reporting results, venous classification systems were often proposed based

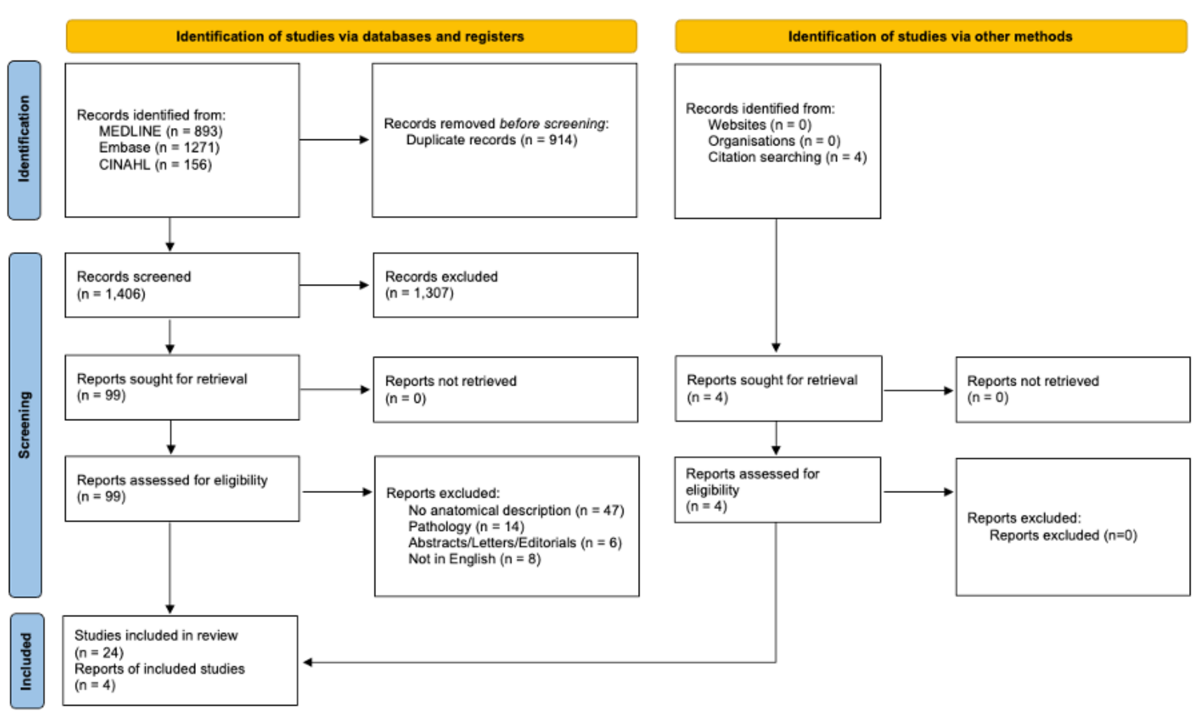

Figure 2 PRISMA flow diagram of study selection.

Table 1 Descriptive overview of included studies reporting quantitative cerebral venous anatomical data

Study	No of subjects	% Men	Mean (range) age, years	Study type (technique)	Reported anatomical data
Ahmed *et al*, 2018[43]	204	47.1	ns (2–75)	Primary (cross-sectional imaging: MRV)	Vein of Trolard: occurrence, laterality
Andrews *et al*, 1989[44]	10	45	27 (2 months–76)	Primary (cadaveric dissection)	SSS: diameter, number of branches Vein of Trolard: linear length, anastomosis angle to SSS
Bruno-Mascarenhas *et al*, 2017[45]	60	50	39.22 (20–59)	Primary (cadaveric dissection)	SSS: diameter, arc length, number of branches Vein of Trolard: occurrence, distance from central sulcus, number of branches
Fang *et al*, 2015[46]	90	58.9	41 (10–78)	Primary (cross-sectional imaging: CTA)	Vein of Trolard: occurrence
Haroun *et al*, 2007a[47]	98	85	27 (2 months–76)	Primary (cross-sectional imaging: MRV)	Vein of Trolard: occurrence
Haroun *et al*, 2007b[48]	110	45	27 (2 months–76)	Primary (cross-sectional imaging: MRI/MRV)	Arachnoid granulations: size, prevalence, morphology
Houck *et al*, 2019[49]	682	40.9	73.9 (SD 5.93)	Primary (cross-sectional imaging: MRI)	SSS: diameter
Ikushima *et al*, 2006[50]	404	40.6	49.8 (2–84)	Primary (cross-sectional imaging: MRI)	Vein of Trolard: occurrence, distance from central sulcus
Naidoo *et al*, 2022[21]	100	40	Median: 30–39 (ns)	Primary (conventional angiography)	Vein of Trolard: occurrence, diameter (variation with age)
Oka *et al*, 1985[28]	10	ns	'Adult'	Primary (cadaveric dissection)	Vein of Trolard: diameter, linear length, number of branches, anastomosis angle to SSS Rolandic vein: distance from central sulcus, linear length, number of branches, anastomosis angle to SSS
Oxley *et al*, 2016[41]	50	40	34.5 (18–73)	Primary (cross-sectional imaging: MRI)	Rolandic vein: diameter, arc length
Santos Silva *et al*, 2014	59	36	ns (13–65)	Primary (conventional angiography)	Vein of Trolard: diameter
Tomasi *et al*, 2021[14]	21	57	71 (51–88)	Primary (cadaveric dissection)	Vein of Trolard: distance from central sulcus
Widjaja *et al*, 2004	50	ns	Median: 5 (0–17)	Primary (cross-sectional imaging: MRV)	Vein of Trolard: occurrence
Yagmurlu *et al*, 2022	8	ns	ns	Primary (cadaveric dissection)	Arachnoid granulations: size, prevalence
Karatas *et al*, 2023[23]	20	40	74 (46–92)	Primary (cadaveric dissection)	Vein of Trolard: diameter, occurrence
Brockmann *et al*, 2011[24]	30	50	46.8 (24–84)	Primary (cross-sectional imaging: CTA)	SSS: diameter, arc length, number of branches
Sampei *et al*, 1996[33]	21	66.7	ns	Primary (cadaveric dissection)	Small cortical vessels: diameter
Han *et al*, 2007[25]	66	59.1	46.8 (11–90)	Primary (cadaveric dissection; DSA)	SSS: number of branches Small cortical vessels: diameter

CTA, CT angiography; DSA, digital subtraction angiography; MRI, magnetic resonance imaging; MRV, magnetic resonance venography; ns, not specified.

on a small patient sample, increasing the chance of bias. No study was excluded due to risk of bias.

Superior sagittal sinus

Anatomical features of the SSS were quantified and reported by seven included studies. Mean SSS diameter ranged from 3.84 mm in the coronal region to 9.9 mm in the mid occipital region (table 2). One study (cadaveric dissection) measured mean SSS arc length to be 338.8 mm and another (imaging study) measured a mean arc length of 256 mm.

Arachnoid granulations present in the SSS were measured in two included studies (see online supplemental material 3). The mean number of SSS tributaries ranged from 11 to 45, with most branches clustered in the anterior frontal region (table 3).

Superior anastomotic vein (vein of Trolard)

Anatomical data relating to the vein of Trolard were reported by 11 included articles. Where prevalence was reported, the vein of Trolard was present in between 26% and 80% of subjects. No study reported a significant difference in the occurrence of the vein of Trolard in one cerebral hemisphere relative to another. The vein of Trolard most commonly overlay the cortex posterior to the central sulcus (table 4).

The mean angle of the anastomosis between the vein of Trolard and SSS ranged from 50° to 103° while the mean venous length was between 1.6 mm and 6.5 mm (see online supplemental material 3).

Central sulcal vein (Rolandic vein)

Anatomical data relating to the central sulcal vein was reported by only two studies. In one study the proximal central sulci vein diameter was measured to be 4.9 mm.

Venous wall composition and mechanical properties

No included study reported findings related to venous wall composition and mechanical properties—namely, wall thickness, compliance, stretch, and compressibility.

Miscellaneous findings

One study identified statistically significant age-related changes in cortical vein diameter, with a notable decrease in diameter beyond the age of 40–49 years, based on conventional

Table 2 Super sagittal sinus (SSS) diameter and arc length measurements

Authors	Location on SSS	Mean±SD diameter, mm	Mean±SD arc length, mm
Bruno-Mascarenhas *et al*, 2017	Coronal	3.97 (ns)*	338.77 (321–357)
	Lambdoid	8.39 (ns)*	ns
	Torcular	9.94 (ns)*	ns
Andrews *et al*, 2018	Mid anterior frontal	4.3 (1.9)	ns
	Mid occipital	9.9 (2.4)	ns
Houck *et al*, 2019	Directly above the confluence of sinuses	6.18 (0.87)	ns
Brockmann *et al*, 2011[24]	Coronal	6.0 (1.9)	256 (16)

*This study measured cadaveric SSS and stated that cross-sectional measurements of SSS were of height and width, as the SSS is triangular in cross-section. Bruno-Mascarenhas *et al* describe arc length measurement as the distance along a long silk thread from the site of origin (glabella) to the site of termination (torcula) of the SSS.
ns, none specified.

angiography.[21] Another study found evidence of myoendothelial tissue at the confluence of the cortical veins with the SSS,[22] suggesting the presence of sphincters which regulate venous flow. Karatas and colleagues identified complex junctions of cortical veins where they adjoin the SSS, while they also quantified the size of parasagittal venous lacunae.[23] Mean venous lacunae measured 5.2×1.5 cm on the right and 5.0×1.7 cm on the left, each connected by multiple slit-like openings to the SSS. One study found that cortical veins at the coronal suture typically drain into lacunae rather than directly into the SSS.[24] However, Han and colleagues reported that, while lacunae often obscure the dural entrances of the cortical veins, lacunae do not directly receive these veins.[25] Instead, they found that the cortical veins sometimes drain into small meningeal veins.

DISCUSSION

The objective of this systematic review was to synthesize current evidence on the anatomy of the superior cortical venous system with implications for endovascular device implantation. To our knowledge, this is the first comparison of cortical venous anatomical measurements from both radiological and cadaveric studies. Our findings show that the anatomical data are limited, inconsistent, and of low quality. We found substantial heterogeneity in the arrangement of the superior cortical veins, with differences found in venous diameter, length, confluence angle between the vein of Trolard and SSS, and location relative to the underlying cortex. Despite study limitations and anatomical variation, the vein of Trolard was consistently reported to be the largest diameter vessel in the superior system, and it was predominantly located posterior to the central sulcus. These findings, along with reports of myoendothelial sphincters and age-related variability, have implications for device design and preoperative planning for endovascular electrode arrays.

Table 3 Superior sagittal sinus (SSS) branching measurements

Authors	Location on SSS	Mean±SD number of SSS branches
Bruno-Mascarenhas *et al*, 2017	Right side	13–19 (ns)*
	Left side	14–19 (ns)*
Andrews *et al*, 2018	Anterior frontal	6.5 (2–14)
	Occipital	1 (0–3)
	Parietal	4 (1–9)
	Posterior frontal	3 (2–6)
Yagmurlu *et al*, 2022	Entire SSS	45 (5.62)†
Brockmann *et al*, 2011[24]	Entire SSS	12.3 (3.3)
Han *et al*, 2007[25]	Entire SSS	11 (ns)

*This study only reports a range of SSS branches across specimen.
†It should be noted that this study reports this number as the total of the following: openings to the SSS from cortical veins, the number of arachnoid granulations, and the number of lateral lacunae.
ns, none specified.

Table 4 Relation of vein of Trolard to central sulcus (reported measures and values from relevant studies)

Authors	Reported measure(s)	Reported value(s)
Ikishima *et al*, 2006	Prevalence of a pre-central vein of Trolard	11%
	Prevalence of a central vein of Trolard (aka Rolandic)	22%
	Prevalence of a post-central vein of Trolard	41%
Bruno-Mascarenhas *et al*, 2017	Average distance (range) in mm from vein of Trolard to central sulcus	Right side 3.90 Left side 4.34
Tomasi *et al*, 2022	Average distance (±SD) in mm between Trolard/SSS confluence and central sulcus midpoint	Right side 6.0 (26) Left side 13.1 (30.1)

Mean diameter of vein of Trolard ranged from 2.1 mm to 3.3 mm in cases of single occurrence (table 5).

Advantages and challenges of implanting endovascular arrays in cortical veins

The development of endovascular BCI devices has transformed the delivery of intracranial electrodes, offering a minimally invasive alternative to traditional surgical methods which require craniotomy. The cortical veins overlying the sensorimotor cortex represent high value targets for these devices as they are subdural and hence in closer association with the cortex than the venous sinuses. To date, endovascular devices have only been placed in the human SSS, capturing neural activity adjacent to areas of motor cortex representing the lower limb. However, one recent study has demonstrated the feasibility of implanting endovascular electrode devices into smaller cerebral vessels.[26] This study also showed the potential to record single unit activity from

Table 5 Vein of Trolard diameter

Authors	Mean vein of Trolard diameter, mm	Range, mm	SD, mm
Oka *et al*., 1985[28]	3.3	2–5	ns
Santos Silva *et al*, 2014	3.32	1.25–8.28	0.11
Naidoo *et al*, 2022[21]	2.14 (single occurrence)	ns	0.472
	2.19 (double occurrence)	ns	0.604
	1.63 (triple occurrence)	ns	ns
Karatas *et al*, 2023[23]	4.4 (right)	ns	ns
	3.8 (left)	ns	ns

Note: Reported diameter, with relevant measure of variability provided (no standard across studies was used).
ns, not specified.

within blood vessels by exploring the arterial system of a rat model. In addition to improved signal quality, a dense network of vessels in proximity to the motor cortex may allow for more implantation sites, leading to greater coverage and better spatial localization of signals.[27]

Despite this breakthrough demonstration of neural recording from within micrometre-scale vasculature, we identified differences in the anatomy of the human cortical venous system that limit translation. Zhang and colleagues performed device implantation just distal to the middle cerebral artery/anterior cerebral artery bifurcation. The branching angle was >100° for both vessels, reducing challenges faced when manoeuvring of the delivery catheter and propelling the device with saline flow. In the cortical venous system, acute confluence angles were reported in multiple studies,[24 28] along with hairpin turns and possibly the emptying of veins into lacunae, complicating device delivery.

Cortical venous walls are also less robust than in the arterial system, with reduced wall thickness, muscularity, and elasticity.[29] Moreover, the cortical veins are especially vulnerable to perforation as they traverse the subdural space, which provides no additional structural support. This vulnerability has been extensively documented in the context of acute subdural hematoma.[30]

Heterogeneity in cortical venous anatomy

Variability is a prominent characteristic of the cortical venous system, unlike the cerebral venous sinuses. The mean number of SSS branches ranged from 14.5 to 45 and confluence angles varied by over 50°. Moreover, the vein of Trolard was identified in fewer than 65% of cases in five studies. The question remains whether this variability is individualized or if a few anatomical phenotypes exist, with practical applications.

Three included studies proposed a classification system for the superior cortical veins.[14 23 28] These systems grouped drainage patterns into five or fewer distinct phenotypes based mainly on network topology or vessel dominance, particularly of the anastomotic veins. All classifications were devised explicitly to support preoperative planning for neurosurgical access to intracranial pathology.

While these classifications may aid neurosurgical planning, we believe they would have limited application in the context of endovascular device implantation. Preprocedural planning for neural recording and subsequent decoding requires a more detailed focus on the underlying cortex. Given the lack of studies reporting phenotypes in these terms, future work may involve creation of a classification system that accounts for cortical regions traversed by each major vessel.

Although a greater engineering challenge, an ability to access small veins within the cortical sulci may obviate concerns about variability. For instance, the vein of the Rolandic sulcus, which we expect is present in a greater number of individuals than certain anastomotic vessels, may be an attractive target for consistent sensorimotor recordings.

Our findings suggest that an individualized approach may be necessary when planning device implantation in cortical veins. Therefore, future clinical workflows may involve prospective planning of training and decoding approaches based on preprocedural imaging.

Implications of cortical vein diameter and position for implantation feasibility

The vein of Trolard was consistently reported to be the largest cortical vein draining into the SSS, with a mean diameter ranging from 2.14 mm to 3.32 mm. Given its size, the vein of Trolard represents the logical first target for endovascular devices implanted in superior cortical veins. Existing endovascular stents are of appropriate diameter for implantation in the vein of Trolard (ie, 2 mm), including stents which have been deployed intracranially.[31 32] This suggests incremental modifications to miniaturize stent electrode arrays may be sufficient to develop an array for implantation in a cortical vessel. However, a novel approach may be required to access the average cortical vessel of the superior venous system. The frontopolar vein, a significant vessel overlying the anterior frontal lobe, was found to have a mean diameter of 1.9 mm with a lower bound of 0.5 mm.[33] Of greater interest are the numerous cortical vessels which bridge the subdural space and are in closer proximity to the cortex. While we have no precise estimate of bridging vein diameter in the cortical venous system, these vessels measure <1 mm in diameter in other areas of the brain.[34]

The vein of Trolard was most commonly identified posterior to the central sulcus (table 4). As its course most commonly overlies the parietal lobe, there may be implications for the decoding of motor intention. Specifically, decoding from the underlying somatosensory cortex (S1) may be more appropriate than the primary motor cortex (M1), the traditional target of motor BCIs.[35] Somatosensory activation has long been recognized to have a role during movement execution and attempted movement.[36] Recent studies using implanted electrode arrays have revealed S1 activation during imagined movement, even in the absence of sensory feedback, indicating that S1 recordings could provide valuable control signals for BCIs.[37] If the vein of Trolard transits more posteriorly across the parietal lobe, further studies have demonstrated decoding of motor imagery from the posterior parietal cortex of human subjects.[38]

Altogether, the vein of Trolard diameter may be appropriate for the delivery of novel stent electrode devices; however, most cortical vessels may not be amenable to this approach based on the lower bound diameter of existing conventional stents. Planning for endovascular device implantation in the vein of Trolard may require consideration of decoding in the parietal lobe. Previous studies have demonstrated the feasibility of decoding motor intent from both anterior and posterior regions.

Age-related changes may influence decisions in younger patients

One included study identified significant changes in cortical vein diameter with age.[21] These changes include a decrease in mean diameter after the fifth decade, which may be caused by stretching of the bridging cerebral veins due to age-related cerebral atrophy.[39] Additionally, there is evidence of increased wall thickness in bridging veins with age.[40] Such changes in vessel diameter may be particularly relevant for younger implant recipients who have decades of potential change following implantation.

Myoendothelial sphincters and complex anatomy present challenges for device delivery

Another included study characterized the presence of sphincters at the confluence of the cortical veins with the SSS.[22] Contractions of myoendothelial tissue at these points may present a challenge when advancing a delivery catheter into the vessels. To mitigate this, the concurrent delivery of a vasodilating agent during implantation may be necessary. Challenges are also presented by slit-like openings in the SSS to venous lacunae, cortical vein drainage into lacunae, and complex junctions of cortical veins, each of which may complicate the delivery of a miniaturized device.

Study limitations

Anatomical data collected in this review were limited, inconsistent, and of low quality, thereby impeding interpretation and preventing meta-analysis. For instance, one study labelled sulcal veins which were superficial to the gyri,[41] making comparisons challenging. These inconsistencies in labelling likely contributed to the variability in measurements reported across studies. Our risk of bias assessment highlighted possible sources of bias, including insufficient reporting of study methods and potential overinterpretation of results. The validity of quantitative comparisons between included studies may have been limited by the methods used for investigation. Formalin fixation, commonly used in cadaveric studies, is known to cause shrinkage and thus an underestimation of measurements.[42] Conversely, cadaveric studies were able to identify vessels of a much smaller diameter than radiological studies, even when using DSA.[25] A notable omission from our findings was data on vessel wall structure and properties. This presents an opportunity for future investigations.

CONCLUSION

This systematic review highlights the significant variability in superior cortical venous anatomy, which has important implications for preprocedural planning and endovascular device implantation. Proposed classification systems are of limited utility as they do not account for the relation of vessels to the underlying cortex. Although the vein of Trolard is the largest draining vessel, its most common location posterior to the central sulcus may require unconventional decoding of motor intention. Overall, further research is necessary to better characterize superior cortical venous anatomy including sulcal vein measurements, vessel wall structure, and relations to underlying cortex. Future work is also needed to characterize the cortical venous anatomy beyond the superior system, alongside the venous anatomy of the deep brain.

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Contributors JB was responsible for developing the review search strategy, inclusion criteria, screening articles, extracting data, analysing data, writing and reviewing the manuscript. AM was responsible for screening articles, extracting data, analysing data, and reviewing the manuscript. FH, KMF, NP, and TJO were involved in interpretation of the results and review of the manuscript.

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