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1 Anatomical Localization

Early studies suggested that the precision of electrode placement for chronic stimulation significantly influences the therapeutic efficacy of motor cortex (primary motor cortex, M1, Brodmann's area 4, BA 4) stimulation (MCS) for pain relief, i.e. relief is generally obtained in the territory corresponding to the cortical region that is stimulated (somatotopically) as per Penfield's motor homunculus. Several problems arise that make this assumption moot, if not untenable.

Contrary to standard teaching, the cortical representation of the lower limb musculature, classically located on the mesial wall of the hemisphere (motor area folding into the longitudinal fissure), actually extends to the lateral surface of the hemisphere (and can thus be targeted extradurally). Experience with other indications, namely Parkinson's disease, shows that targeting part of the surface of M1 on one side only is enough to improve symptoms body-wide (chapter 10) and cases of bilateral pain relief exist from unilateral M1 stimulation (chapters 8-9). Besides, a large portion of BA4 occupies the posterior wall of the precentral gyrus in the depth of the anterior bank of the central sulcus, with only a relatively small dorsomedial portion found on the exposed surface of the precentral gyrus. Therefore, the epidural approach should be inadequate for the stimulation of motor cortical targets, which is not the case.

Methods of localizing cortical landmarks – e.g. the central sulcus (CS), a.k.a. Rolando's Fissure, which separates the motor strip (precentral gyrus) anteriorly from the primary sensory cortex posteriorly, and the lateral (Sylvian) sulcus (LS)-based on the relationship of cortical fissures and convolutions as they project to the cranial bony structures have been developed and utilized since the XIX century ([Box 1.1](#)). These basic craniocerebral localization techniques play an important role in therapeutic electrical cortical stimulation. In this chapter, I present the more well-known and widely utilized techniques for the localization of the CS and the LS, as well as the more recent techniques of identifying the precentral knob, or the hand representation, in M1 for the purpose of therapeutic ICS.

Pterion: region of approximation of the frontal, parietal, temporal and sphenoid (greater wing) bones; it lies approximately 2 finger-breadths above the zygomatic arch, and a thumb's breadth behind the frontal process of the zygomatic bone.

Asterion: junction of the lambdoid, occipitomastoid and parietomastoid sutures. It overlies the junction of transverse and sigmoid sinus.

Lambda: junction of the lambdoid and sagittal sutures.

Stephanion: junction of the coronal suture and the superior temporal line.

Glabella: the most forward projecting point of the forehead at the level of the supraorbital ridge in the Midline.

Opisthion: the posterior margin of the foramen magnum in the midline.

Box 1.1: Craniometric Points

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1.1 Craniometric Methods

These are reviewed in depth by Park et al (2009). These are the methods of Broca-Championnière (1896), Reid (1884), Poirier (1891) and Taylor-Haughton (1900) (Fig.1.1-1.4). In 1980, the Taylor-Haughton line was re-evaluated using CT imaging for localization of the CS and LS (Taylor et al 1980). The study concluded that the Taylor-Haughton line provides a good approximation of the CS and *“the motor and sensory cortex can be accurately located for planning surgical procedures for anatomic studies”*. In 1995, Albert L. Rhoton, Jr. published his procedure for localizing CS and LS based on a large number of cadaver studies (Rhoton 2002, Reis et al 2008) (Fig.1.5).

Fig. 1.1: Top and lateral views of the skull illustrating Broca-Championnière method of central sulcus or Rolandic fissure localization. B: bregma (black dot), EOA: external orbital apophysis, IE: inferior end (inferior Rolandic point), RL: Rolandic line (solid black line), SP: superior point (superior Rolandic point), SS: sagittal suture, Z: Zygomatic arch line (white dashed line). Here, *“l’extrémité inférieure”* or the inferior Rolandic point is localized by determining a 7-cm line which starts at the external orbital apophysis of the frontal bone, parallel to the zygomatic arch, and *“le point supérieur”* or the superior Rolandic point (SRP) is located on average 4.7 cm behind the bregma. The central sulcus is located on the line connecting the two points.

Fig. 1.2: Top and lateral views of the skull illustrating Reid's method of central sulcus or Rolandic fissure localization. EAP: external angular process of the frontal bone (black dot), LF: longitudinal fissure, MPL: mastoid process line, PE: parietal eminence (black square), PEL: pre-external auditory meatus line, RBL: Reid's base line, RF: Rolandic fissure (solid black line), SF: Sylvian fissure. The base line, known as Reid's base line, is defined as that which *"runs through the lowest part of the infraorbital margin and the middle of the external auditory meatus"*. The Sylvian fissure is localized by drawing a line *"from a point one inch and a quarter behind the external angular process of the frontal bone to a point three-quarters of an inch below the most prominent part of the parietal eminence"*. The Rolandic fissure is localized by drawing a pair of perpendicular lines to Reid's base line. The first line is drawn *"from the depression in front of the external and auditory meatus"* and the second line is drawn *"from the posterior border of the mastoid process at its root"*. This creates a *"four-sided fig."*, bounded above and below by the lines for the longitudinal fissure and horizontal limb of the fissure of Sylvius respectively, and in front and behind by the two perpendicular lines. The diagonal line of this four-sided fig. represents the fissure of Rolando.

Fig. 1.3: Top and lateral views of the skull illustrating Poirier's method of central sulcus or Rolandic fissure localization. IRP: inferior Rolandic point (black star), ML: midline, RL: Rolandic line (solid black line), SRP: superior Rolandic point (black open square), 50%: halfway point between nasion and inion. The superior Rolandic point is 2 cm behind the midpoint between the nasion and inion on the midline. The inferior Rolandic point is 7 cm above the zygomatic arch immediately anterior to the tragus, perpendicular to the zygomatic arch. The LS lies on the nasion-lambda line which starts at the temporal canthus to a point 1 cm anterior to the lambda on the midline.

Fig. 1.4: Top and lateral views of the skull illustrating Taylor-Haughton method of central sulcus or Rolandic fissure localization. Central sulcus (RL) is the line connecting the SRP and IRP. IRP: inferior Rolandic point (black star), NI: Nasion-inion line, OTA: orbito-temporal angle (solid black square), PAL: pre-auricular line, PAP: pre-auricular point (solid black dot), RL: Rolandic line (black line), SL: Sylvian line, SRP: superior Rolandic point (open black square), Z: zygomatic arch (upper margin) line, 50%: halfway point on the naso-inion line (open black dot), 75%: three-quarters point on the nasion-inion line. *"In the adult take a point (superior Rolandic) three-quarters of an inch behind the centre of the naso-inion line. This will usually be found to correspond to 53 to 55 per cent of the naso-inion distance, measuring from before backwards. The lower Rolandic point is found by erecting a perpendicular to the upper margin of the zygoma, starting from the pre-auricular point to meet the Sylvian line. Should, however, the upper margin of the zygoma be difficult to determine, the perpendicular (pre-auricular line) may be erected on a line connecting the center of the infra-orbital margin with the center of the external auditory meatus or auricular point. The Rolandic line may now be drawn by connecting these two points".*

Fig. 1.5: Top and lateral views of the skull illustrating the method of CS and LS localization as described by Dr. Albert L. Rhoton, Jr. CS: central sulcus (solid black line), FZL/SF: frontozygomatic line / Sylvian fissure, IRP: inferior Rolandic point (black star), NI: Nasion-inion line, SRP: superior Rolandic point (open black square), 50%: halfway point on the nasion-inion line, 75%: three-quarters point on the nasion-inion line. The LS is located on the frontozygomatic line which connects the frontozygomatic suture to the 75% point of the naso-inion line. The SRP is located 2 cm behind the 50% point of the naso-inion line. Another line is drawn from the midportion of the zygomatic arch to the SRP where IRP is the point of intersection with the LS or frontozygomatic line.

1.2 Image-Guided Methods

Kido et al (1980), using CT axial views of cadaveric brain specimens with specially marked superior frontal, precentral and central sulci, as well as that of live patients (86 hemispheres, 50 patients), concluded that the approximate location of CS - even when it cannot be visualized on the scan- is a point 4.6 cm behind the coronal suture and 2.1 cm from the midline, and then drawing a line through this point at an angle

of 67.9° from the midline (Fig.1.6). However, they did not extend their localization to a specific landmark, such as the precentral knob (see ahead). Using CT and MRI axial views, Iwasaki et al (1991) described a method of identifying the precentral and postcentral gyri on the basis of the medullary branches of the cerebral white matter. The superior frontal gyrus, which runs parallel to the sagittal plane, will form an angle with the precentral gyrus; the CS will be localized posterior to it. Using magnetic resonance (MR) sagittal images, Naidich et al (1995) described the cingulate sulcus as a landmark for recognition of the CS. The cingulate sulcus can be followed in a midline sagittal image posteriorly, where its ascending segment is known as the marginal ramus or sulcus. The notch formed immediately anterior to it (at the vertex) is formed by the central sulcus. The MR lateral sagittal image is also used to localize the CS. The anterior horizontal and anterior ascending rami of the inferior frontal gyrus are identified. They have a Y-shaped appearance. The major descending sulcus immediately posterior to the “Y” is the precentral sulcus, followed posteriorly by the CS. The precentral sulcus is formed by two discontinuous grooves called the inferior precentral sulcus (Ebeling et al 1989) and the superior precentral sulcus. The CS courses approximately parallel to the zigzag precentral sulcus and almost never intersects the Sylvian fissure. Rather, the bottom end is closed by the fusion of the precentral and postcentral gyri. The CS runs uninterrupted in 92% of the cases, while the precentral sulcus is regularly interrupted in 100% of the cases (Yasargil 1994).

Fig. 1.6: Top view of the skull illustrating the position of the central sulcus based on the measurements of Figure 8 in Kido et al (1980). The lines and measurements are superimposed onto the skull to estimate the location of the central sulcus.

Yousry et al (1997) proposed a new landmark corresponding to the neural elements involved in motor hand function. Using functional MRI, the segment of the precentral gyrus that most often contained motor hand function was a knob-like, broad based, posterolaterally directed structure. It usually (90% of cases) has an inverted omega

(Ω) shape and sometimes a horizontal epsilon (ϵ) shape in the axial plane with a mean diameter of 1.4 cm. On average it is located about 23 mm from the midline, just posterior to the junction of the superior frontal sulcus with the precentral gyrus and 19 mm from the lateral surface. In the sagittal plane, this knob has the form of a posteriorly directed hook (92% of the cases), with a mean depth and height of 17 and 19 mm, respectively. It is located in the sagittal plane on the same section on which the insula can be identified, perpendicular to its posterior end. On the cortical surface of cadaver specimens, this precentral knob corresponded precisely to the characteristic ‘middle knee’ of the CS that has been described by various anatomists in the XIX century. This “precentral” knob is a reliable landmark for identifying the precentral gyrus directly, in particular the neural elements involved in motor hand function (Boling et al 1999). It faces and forms the ‘middle knee’ of the CS, is located just at the cross point between the precentral sulcus and the CS, and is therefore also visible on the cortical surface. Based on measurements from the MRI, this hand area can thus be localized to an area 30 mm lateral to the midline and posteriorly following the superior frontal sulcus until it intersects with the precentral sulcus. Above this knob, the cortical portion subserving the chest and inferior limb can be found, with extension to the medial edge of the hemisphere or even in the interhemispheric part of the strip.

Classically, the CS has been described as having three curves in the axial plane: the superior and inferior genua, which are convex anteriorly, and the middle genu, which is convex posteriorly. A 43-patient study confirmed this arrangement (Campero et al 2011). On anatomic specimens, this Ω (Omega) is 11.2 ± 3.35 mm in height, on average, and 18.7 ± 2.49 mm in width, at the base. The average distance from the medial limit of the Ω to the medial edge of the hemisphere is 24.5 ± 5.35 mm. Most importantly, the anatomical identification of the CS on a normal brain approaches 100%. Caulo et al (2007) obtained structural brain MR images from 257 right-handed healthy men and women and identified new variants of the hand M1 besides the omega and epsilon shapes described above. In particular they observed a medially asymmetric ϵ (epsilon), a laterally asymmetric ϵ and a null variant in respectively 2.9%, 7% and 1.8% of the study subjects (Fig.1.7). Also, the ϵ variant was twice as frequent in men, and an interhemispheric concordance for morphologic variants was observed only for women.

On a CT, the precentral knob on M1 is consistently located 45.1 ± 5.2 mm posterior with respect to the coronal suture line and 33.9 ± 3.4 mm lateral to the midline on the right hemisphere, and 44.6 ± 5.7 mm posterior and 33.2 ± 2.5 mm lateral on the left hemisphere (Park et al 2007). This can also be transposed onto the skull to provide the approximate location of the precentral knob on M1 with respect to the external skull markings (Fig.1.8). The approximate location of the precentral knob based on CT is in agreement with the previously described methods and appears capable of replacing MR scanning when this is not available or contraindicated (e.g. in the presence of an implanted cardiac or neural pacemaker, metal debris or metal fragments in the body).

Fig. 1.7: Schematic representation of the criteria used for morphologic classification and corresponding MR image of a typical example. The position of the third fissure, which segments the knob, modifying its appearance from an omega to an epsilon in the lateral, central, or medial part of the hand knob indicates a medially asymmetric epsilon, epsilon, and laterally asymmetric epsilon, respectively. To distinguish an omega from a null, the height of the knob must be greater than the thickness of the precentral gyrus measured at the base of the knob. If the height is smaller than the thickness, the HMC is classified as null. Multiplanar reformatted MR imaging axial sections were obtained from left hemispheres 50 ± 2 mm above the Talairach ACPC plane. The red area in the MR images highlights the morphologic variant (from Caulo et al 2007).

Fig. 1.8: Top view of the skull illustrating the position of the precentral knob of the primary motor cortex with respect to skull landmarks, based on the measurements from CT of the brain (Park et al 2007). PCK: precentral knob.

Anatomical localization of MI can also be accomplished using image-guided neuronavigation systems, based on standard MRI, functional MRI (fMRI), positron emission tomography (PET) or magnetoencephalography (MEG) (Sobel et al 1993, Mogilner and Rezai 2001) (Fig.1.9). 3D image-guided navigation systems help to determine the exact location of anatomical reference points, CS, LS, interhemispheric sulcus, superior and inferior frontal sulci, which can be clearly visualized on the reconstructed images. The superior frontal sulcus separates the superior frontal gyrus from the middle frontal gyrus, coursing anterior to posterior and perpendicular to the precentral sulcus. The next sulcus posteriorly may be identified as the CS. Referring to the cortical representation of body parts (cortical homunculus), the face area lies below the inferior frontal sulcus, the neck at the level of the inferior frontal sulcus, the arm and hand between the inferior and superior frontal sulci and the upper chest at the level of the superior frontal sulcus (Velasco et al 2002).

Fig. 1.9: Stereotactic planning in different views (3D) for targeting fMRI activation areas (images courtesy of Prof. B.Pirotte)

These structures can be visualized by oblique MRI sections parallel to a plane from the sylvian to the interhemispheric fissure in the axial views (the Rolandic fissure is the deepest mesiolateral sulcus extending from the sagittal to the Sylvian fissure), a feat not possible with conventional MRI views (Velasco et al 2002). By applying vitamin E capsules glued onto the skin overlying vertex, inion, nasion and pterion and superimposed on the oblique MRI sections, Velasco et al (2002) found that the Rolandic fissure begins mesially at a point 3.90-3.96 cm behind the vertex and with a postero-anterior trajectory over the convexity toward a point 0.3-0.9 cm above the angle formed by the zygomatic arch and the external orbital rim. The Rolandic fissure follows an angled trajectory of about 45° with respect to the sagittal plane (i.e. it is oblique to the cortical surface), its course being rather tortuous with two distinct and constant curves, one with an anterior concavity at the level of the superior frontal sulcus and another with an anterior convexity between the superior and the inferior

frontal sulci. The oblique course may be relevant when the place of an extradural MI stimulator is decided on the basis of N20-P20 reversal. The vertex-pterion line invariably lies anterior to the upper two thirds of the motor strip, which may be critical when implanting stimulating paddles parallel to the Rolandic fissure in order to target arm, pelvis, leg and thorax territories. On the other hand, cerebral localization using the 10-20 EEG system is not adequate (Homan et al 1987), although some surgeons use it for localization purposes.

From a stereotactic perspective, the strikingly constant association of the CS with the midcallosal plane must be stressed. Lehman and colleagues (1992) demonstrated the reliability of a midcallosal line to intersect the inferior CS. Talairach et al (1993) recognized that most of the CS lies between two vertical planes extending from the AC and PC. The most superior aspect of the CS arises just behind the PC and the inferior sulcal limit just in front of the AC. The y coordinate (which determines the anteroposterior location) has the smallest range of values for face and tongue sensory activations consistent with the fixed position of the inferior CS in relation to midline commissural fiber bundles (Boling et al 2002).

A special reference should be made to the portion of the primary sensory cortex responsible for facial and buccal sensation in reference to cortical stimulation for facial pains. In open neurosurgical approaches, the tongue sensory area is easily recognized as a triangular gyral configuration in the most inferior aspect of the postcentral gyrus, just above the Sylvian fissure. The distance between the Sylvian fissure and the thumb-hand area is no more than 3 cm (Boling et al 2002). Anterior tongue sensory function is localizable to the superior aspect of the triangle. Lower face sensation is subserved by the narrow portion of the postcentral gyrus, which is situated immediately above the tongue area. The apex of the tongue sensory area thus narrows immediately into a thin segment of the postcentral gyrus, which is the substratum of low face sensation (Boling et al 2002). The tongue sensory area is the only area where the postcentral sensory gyrus is not thinner than the precentral motor cortex. When placing an extradural stimulating strip straddling the motor and sensory cortex, it is important to bear in mind this particular triangular anatomic configuration.

1.3 Conclusions

Individual variability causes the motor strip to lie anywhere from 4 to 5.4 cm behind the coronal suture, and landmark- based linear measurements may vary by up to 2 cm. This is mainly due to the natural individual variability and must be kept in mind when linear measurements based on anatomical landmarks from CT images are to be used to localize the precentral knob area.

Since neuronal populations in M1 active in movements of different fingers overlap extensively and control of a finger utilizes a network distributed throughout the hand

area, this suggests that the position of the stimulating electrode is not critical as long as it is not close to the boundary of the hand representation. The average medio-lateral span of the hand representation in M1 along the CS is 24-36mm, the vertical span being 36-56 mm.

One might think that the advent of frameless guidance system or neuronavigation has largely replaced localization relative to bony landmarks. Nonetheless, Reis et al (2008) concluded that the above-described classic craniocerebral topographic procedures are reliable methods for localizing CS and LS as well as associated landmarks and –most cogently- that modern imaging and neuronavigation have improved upon these methods by only 1-3 mm! Velasco et al (2008) too found that rolandic fissure localization by external landmarks is satisfactory (mean error: 1.6 mm, range: 0-7 mm).

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