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## 2.1 Neuroanatomy and Cortical Landmarks of Functional Areas

Prior to any type of functional mapping, a profound knowledge of neuroanatomy is mandatory. Focusing on the clinical applications of fMRI, this chapter will present methods to identify characteristic anatomical landmarks and describe the course and shape of some gyri and sulci and how they can be recognized on MR imaging. As anatomy will be presented in neurofunctional systems, some redundancy is desired in order to course over cortical landmarks. If fMRI is not performed during clinical routine imaging, usually a 3D data set is acquired to overlay the results. Nowadays, fMRI is performed using echo planar imaging (EPI) with anisotropic distortion, whereas 3D T1-weighted data sets, such as MPRage (magnetization-prepared rapid acquisition gradient echo) or SPGR (spoiled gradient-recalled acquisition in steady state) sequences, are usually isotropic. Normalization of the fMRI data may reduce this systemic error to some extent that is more pronounced at the very frontal aspect of the frontal lobe and the very posterior aspect of the occipital lobe. However, for individual data,

normalization and overlaying fMRI results on anatomy remain crucial. No two brains, not even the two hemispheres within one subject, are identical at a macroscopic level, and anatomical templates represent only a compromise (Devlin and Poldrack 2007). Usage of templates like the Talairach space (based on the anatomy of one brain) or the MNI template (based on 305 brains) can cause registration error as well as additional variation and reduce accuracy; indeed, it does not warrant the shammed anatomical precision in the individual case.

### 2.1.1 Sensorimotor Cortex

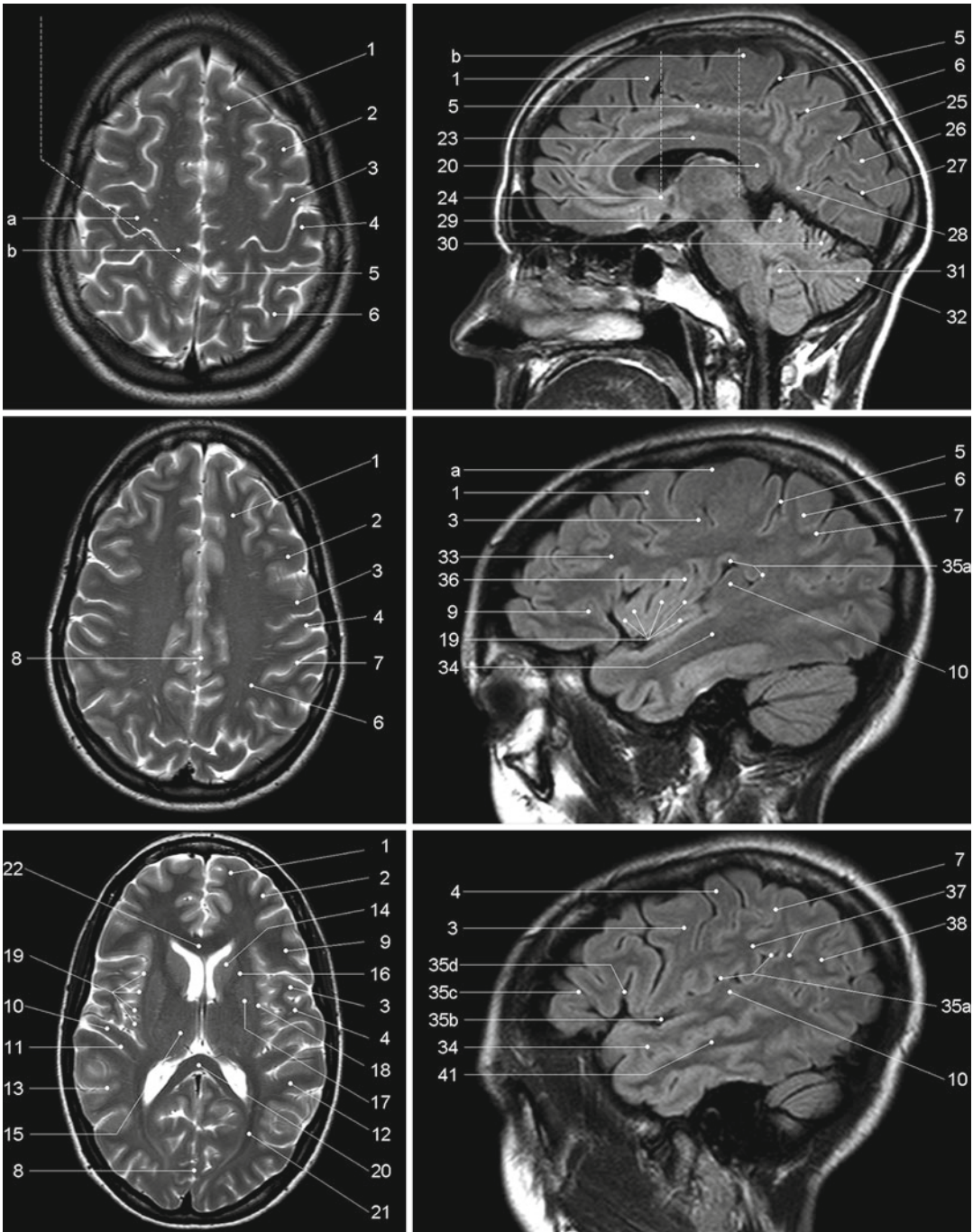
#### 2.1.1.1 Transverse Sections

There are various methods to identify the precentral gyrus (preCG; [3]), the central sulcus (CS) and the postcentral gyrus (postCG; [4]). From a craniocaudal point of view, the sensorimotor strip follows (from the apex to the Sylvian fissure [35b]) a medial-posterior-superior to lateral-anterior-inferior course. The precentral gyrus [3] fuses with the superior frontal gyrus (SFG; [1]) at the very upper convexity (Ebeling et al. 1986; Kido et al. 1980; Naidich et al. 1995; Ono et al. 1990). This can be well depicted on transverse sections (see Figs. 2.1 and 2.2). The precentral gyrus [3] is the most posterior part of the frontal lobe that extends inferiorly to the Sylvian fissure [35b]. The precentral gyrus [3] is thicker than the postcentral gyrus [4] in anterior-posterior (ap) dimension (Naidich et al. 1995) as is the grey

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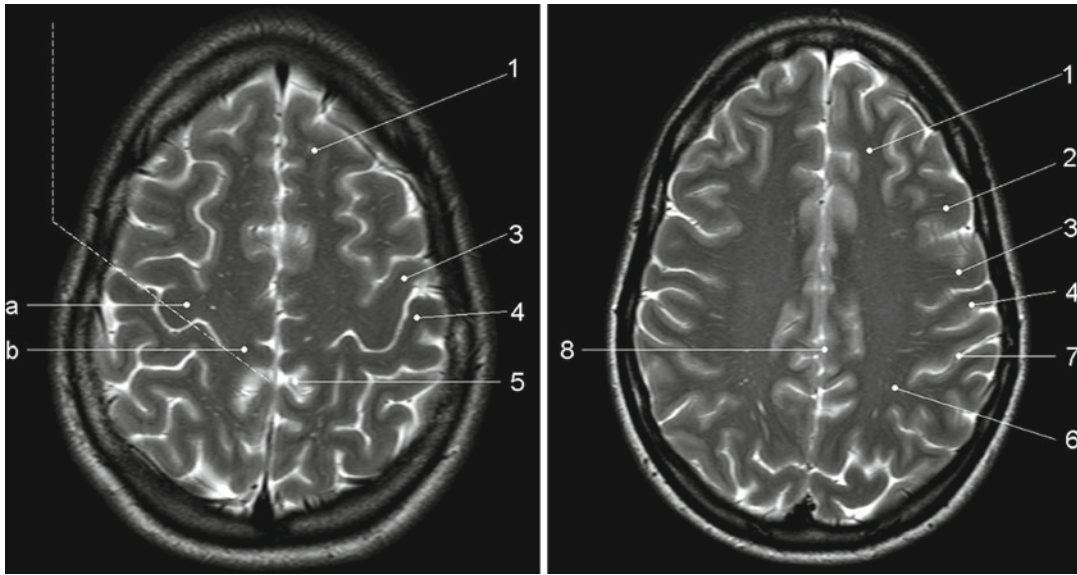
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**Fig. 2.1** Overview of the used sections. The numbers are explained within the text as well as in the other figure legends in detail

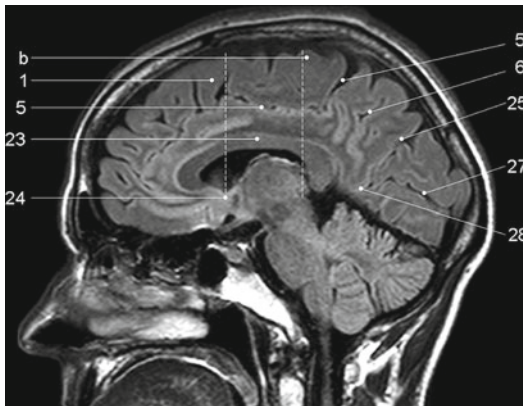
matter (Meyer et al. 1996). At the apex, the pre-[3] and postcentral gyri [4] form the paracentral lobule [b] as they fuse. Making a little detour to a

lateral view (see Fig. 2.3), the cingulate sulcus [5] ascends at the medial interhemispheric surface dorsal to the paracentral lobule (pars marginalis)



**Fig. 2.2** Axial T2-weighted TSE MR images. 1 superior frontal gyrus, 2 medial frontal gyrus, 3 precentral gyrus, 4 postcentral gyrus, 5 “pars bracket”, cingulated sulcus, 6

precuneus, parietal lobe, 7 intraparietal sulcus, 8 interhemispheric fissure, *a* hand knob, *b* paracentral lobule



**Fig. 2.3** Sagittal FLAIR image at the midline. 1 superior frontal gyrus, 5 “pars bracket”, cingulate sulcus, 6 precuneus, parietal lobe, 23 body of the corpus callosum, 24 anterior commissure, 25 parietooccipital sulcus, 27 calcarine fissure, *b* paracentral lobule, 28 cuneal point

[*b*] and thus separates it from the precuneus [6]. This intersection can be appreciated on axial sections as the “bracket” sign (see Fig. 2.2; Naidich and Brightbill 1996) that borders the postcentral gyrus [4]. Somatotopographically, the apex harbours the cortical representation the lower extremity (Penfield and Rasmussen 1950). Following its course along the superficial

convexity (from medial-posterior-superior to lateral-anterior-inferior), the cortical surface of the precentral gyrus increases at its posterior margin, building the omega-shaped motor hand knob ([*a*]; Yousry et al. 1995, 1997). Within this primary motor cortex (M1) of the hand, there is an additional somatotopic order of the individual digits (with interindividual overlap and variation). From medial to lateral, the hand is organized beginning with digit 5 (D5), to the thumb representation (D1) being the most lateral (Dechent and Frahm 2003). The motor hand knob [*a*] is another typical landmark of the precentral gyrus [3]; however, as the CS and the postcentral gyrus [4] follow this course, there is also an omega-shaped structure in the postcentral gyrus (harbouring the somatosensory hand area). However, as described above, the ap-dimension of the postcentral gyrus [4] is smaller compared to the precentral gyrus [3], thus often enabling a differentiation. Somatotopographically, the cortical somatosensory representation follows the distribution of the precentral gyrus [3] (Penfield and Rasmussen 1950; Overduin and Servos 2004). Lateral to the SFG [1], the medial frontal gyrus [2] zigzags posteriorly and points towards the motor

hand knob [a]. Beginning at this “junction” and lateral-inferior to this landmark, the ap-diameter of the preCG [3] decreases, but it increases again along the lower convexity. This has already been recognized by Eberstaller (1890). Using modern imaging techniques, the diameter had been measured and the previous findings validated that the biggest diameter of the preCG [3] is found at the lower portion of the gyrus adjacent to the Sylvian fissure [35b] (Ono et al. 1990). This is the primary motor cortex (M1) of lip representation and tongue movements. In the axial sections, there is neither a typical shape or landmark of the gyrus, nor does measuring from the motor hand area or the ac (anterior commissure) help us to describe the location precisely. This can be solved on sagittal sections (see below).

Previously, the anatomy of the frontal lobe has been described partially. As the course of the medial frontal gyrus [2] can be followed nicely on axial sections, the lateral inferior aspect of the frontal lobe represents the inferior frontal gyrus. Anterior to the preCG [3], the prefrontal motor areas can be found. The inferior frontal gyrus borders and overhangs the insula [19] anteriorly. This part is the frontal operculum [9] harbouring the motor speech area of Broca (see below sagittal sections). The lateral ventricles with its anterior and posterior horn can easily be depicted on axial sections due to its typical form and typical signal caused by corticospinal fluid (CSF, see Figs. 2.1, 2.5 and 2.6). Their shape is formed through the head of the caudate nucleus [10] lateral to the anterior horn, the thalamus [11] lateral at its waist (III. ventricle) and posteriorly by the fibres of the anterior-posteriorly running optic radiation [21] and left-right running fibres of the splenium [20] (see Figs. 2.5 and 2.6). Lateral to these structures, descending corticospinal fibres pass the internal capsule [16] and follow a certain somatotopic organization. The internal capsule is framed medial by the head of the caudate nucleus [10], the third ventricle and the thalamus [11] (at the posterior aspect of the third ventricle) and lateral by the globus pallidus [17]. From medial to lateral towards the insula [19], the globus pallidus, putamen and claustrum within the lentiform nucleus [17] can be differentiated. In the anterior

limb and the genu of the internal capsule, [16] corticospinal fibres from the tongue, lip and face descend, whereas in the posterior limb, fibres from the upper extremity, body and finally lower extremity are found.

### 2.1.1.2 Sagittal Sections

Previously sagittal sections have been described at the interhemispheric surface (see Fig. 2.3). The corpus callosum [20, 22, 23] represents the biggest connection between the two hemispheres. The frontal aspect is the genu [22], the medial part is the body [23] and the most rostral part is the splenium [20]. The corpus callosum encases the lateral ventricles. At the base, the anterior commissure (ac; [24]) can be identified as a roundish structure. Sometimes, the posterior commissure (pc) can also be defined, which represents a bundle of white fibres crossing the midline, at the dorsal aspect of the upper end of the cerebral aqueduct. Previously slice orientation of most fMRI studies had been performed according to this ac-pc line in order to have a reference system.

From the base to the apex, the corpus callosum is abutted by the callosal sulcus and the cingulate gyrus. The gyrus abutting the cingulate sulcus [5] is the medial part of the SFG [1]. In the region (at the medial cortical surface) framed by vertical lines perpendicular to the ac (Vac) or pc (Vpc; see Fig. 2.3), the supplementary motor area (SMA) is harboured in the cingulate gyrus and superior frontal gyrus. As described above, the cingulate sulcus [5] ascends at the medial interhemispheric surface (see Fig. 2.3) dorsal to the paracentral lobule ([b]; pars marginalis) and thus separates it from the precuneus [6]. This intersection can be nicely appreciated on axial sections as the “bracket” sign (see Fig. 2.2; Naidich and Brightbill 1996) that borders the postcentral gyrus [4]. The postcentral gyrus is already a part of the parietal lobe. The precuneus [6] is located dorsal to the postcentral sulcus. There is another important landmark that separates the parietal lobe from the occipital lobe (cuneus [26]), the parietooccipital sulcus [25]. It can be easily recognized in sagittal views (see Fig. 2.3), as the dorsal sulcus that follows an inferior-anterior to superior-posterior course, posterior to the ascending



part of the cingulate sulcus [5]. It is advisable to follow one of these structures moving laterally through the brain in sagittal sections. Once the Sylvian fissure [35b] can be identified, anatomical landmarks are again easy to define.

In midsagittal sections (see Fig. 2.6), the motor hand knob [a] can again be recognized as a “hook” that rises out of the parenchyma and points dorsally. Further, laterally the sensorimotor cortex overhangs the insula [19]. The Sylvian fissure [35b] that separates the frontal lobe and the temporal lobe has an inferior-anterior to superior-posterior course. At its anterior margin, it ascends into the anterior horizontal ramus [35c] and more dorsally into the anterior ascending ramus [35d] of the frontal operculum [9] that also overhangs the anterior aspect of the insula [19]. The anterior horizontal ramus [35c] separates the pars orbitalis [40] from the pars triangularis [39], whereas the anterior ascending ramus [35d] separates the pars triangularis [39] from the pars opercularis [9] of the frontal operculum of the inferior frontal gyrus and thus forms an “M” (Naidich et al. 1995). The pars opercularis [9] of the frontal operculum of the inferior frontal lobe harbours Broca’s area. At its posterior margin, the pars opercularis is delimited by the anterior subcentral sulcus. At the base of the sensorimotor strip, the precentral [3] and postcentral gyrus [4] fuse (Eberstaller 1890; Ono et al. 1990). This junction is delimited dorsally by the posterior subcentral sulcus. Movement of the lips or tongue induce an increase in BOLD signal at this portion (Fesl et al. 2003, own observations). The base of the sensorimotor area has, depending on anatomical variations, a “K” or an “N” shape that is built by the anterior subcentral sulcus and inferior precentral sulcus, the precentral gyrus, posterior subcentral sulcus, postcentral gyrus and postcentral sulcus that again borders the angular gyrus [38] (Eberstaller 1890; Ono et al. 1990, own observations; see Fig. 2.6). The posterior part of the Sylvian fissure separates – following its superior-posterior course – and ascends into the posterior ascending ramus [35a] flanked by the anterior and posterior aspect of the supramarginal gyrus [37] that has a horse-shoe appearance.

## 2.1.2 The Insula

The insula [19] is covered by the superior temporal gyrus [34], the frontal operculum [9] and the base of the sensorimotor strip. Its anatomy is best depicted in sagittal sections (see Fig. 2.6).

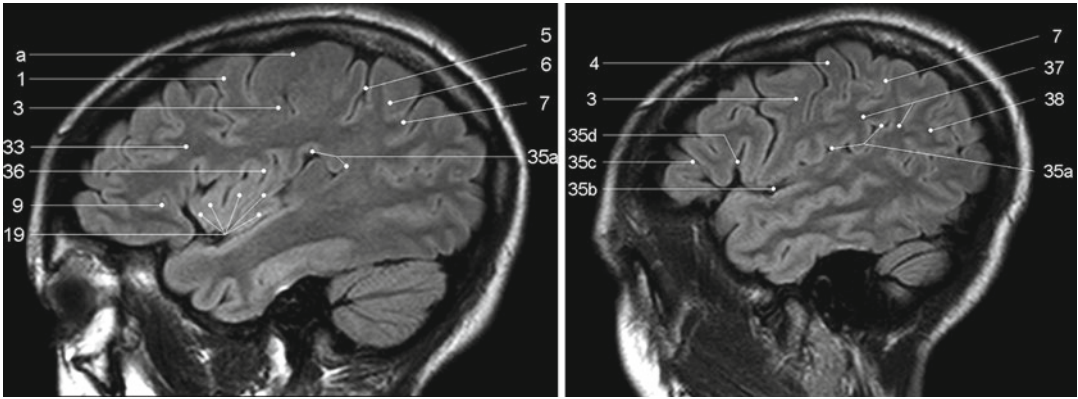
### 2.1.2.1 Sagittal Sections

The insula [19] is separated by the CS [36] that runs from superior-posterior towards the inferior-anterior located apex of the insula into an anterior lobule and a posterior lobule (see Fig. 2.6). The anterior lobule consists of three gyri (anterior, medial and posterior short insular gyri); the posterior lobule consists of two gyri, the anterior long insular gyrus and the posterior long insular gyrus separated by the postcentral gyrus (Naidich et al. 2004).

From a neurofunctional point of view, the insula has various functional areas. The anterior lobule was found to cause word-finding difficulties during electrical stimulation in epilepsy surgery (Ojemann and Whitaker 1978a, b) and to be responsible for speech planning (Wise et al. 1999; Price 2000). Speech apraxia is induced through lesions in the left precentral gyrus of the insula (Dronkers 1996; Nagao et al. 1999), whereas the right anterior lobule becomes activated during vocal repetition of nonlyrical tunes (Riecker et al. 2000). Stimulation of the right insula increases sympathetic tone, and stimulation of the left insula increases parasympathetic tone (Oppenheimer 1993), possibly playing a role in cardiac mortality in left insular stroke. Finally visual-vestibular interactions have been found (Brandt et al. 1998) to name a few systems.

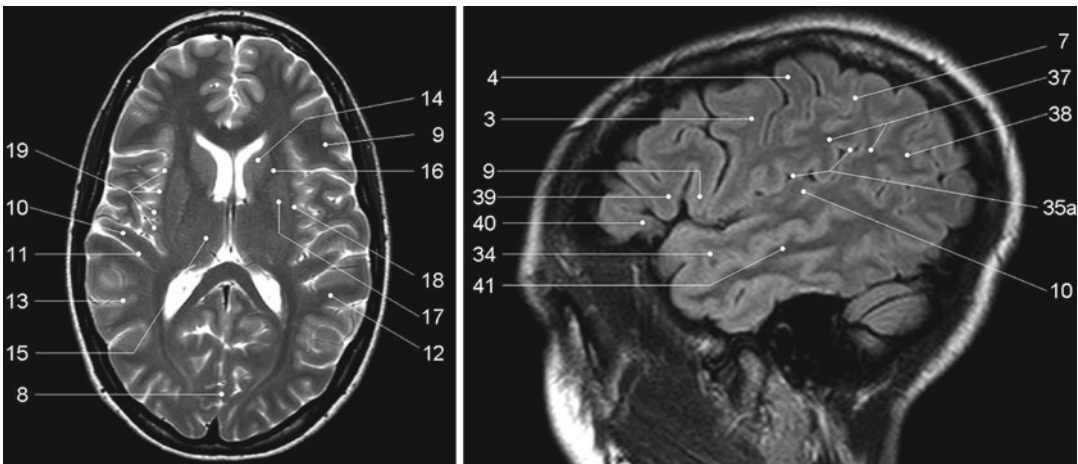
### 2.1.2.2 Transverse Sections

The insular cortex [19] is delimited medially by the globus pallidus, putamen and claustrum (lentiform nucleus [17]) and separated by a small border of white matter (extreme capsula [18]). The gyri can be differentiated by counting each knob starting ventrally at the anterior peri-insular sulcus that abuts the pars opercularis [9] of the frontal operculum of the inferior frontal gyrus (see Figs. 2.4 and 2.5). Five knobs can be defined (anterior, medial and posterior short insular gyri and anterior and posterior long insular gyri).



**Fig. 2.4** Sagittal FLAIR images. 1 superior frontal gyrus, 3 precentral gyrus, 4 postcentral gyrus, 5 “pars bracket”, cingulate sulcus, 6 precuneus, parietal lobe, 7 intraparietal sulcus, 9 pars opercularis, inferior frontal lobe, frontal operculum, 19 insula (anterior and posterior short insular gyri, anterior and posterior long insular gyri), 33 medial

frontal gyrus, 35a posterior ascending ramus of the Sylvian fissure, 35b Sylvian fissure, 35c anterior horizontal ramus of the Sylvian fissure, 35d anterior ascending ramus of the Sylvian fissure, 36 central sulcus of the insula, 37 supramarginal gyrus, 38 angular gyrus, a hand knob



**Fig. 2.5** Axial T2-weighted TSE MR and sagittal FLAIR images. 3 precentral gyrus, 4 postcentral gyrus, 7 intraparietal sulcus, 8 interhemispheric fissure, 9 pars opercularis, inferior frontal lobe, frontal operculum, 10 Heschl’s gyrus, 11 Heschl’s sulcus, 12 planum temporale, 13 superior temporal sulcus, 14 head of the caudate nucleus, 15 thalamus, 16 internal capsule, 17 globus pallidus, putamen, claustrum (lentiform nucleus), 18 extreme capsule,

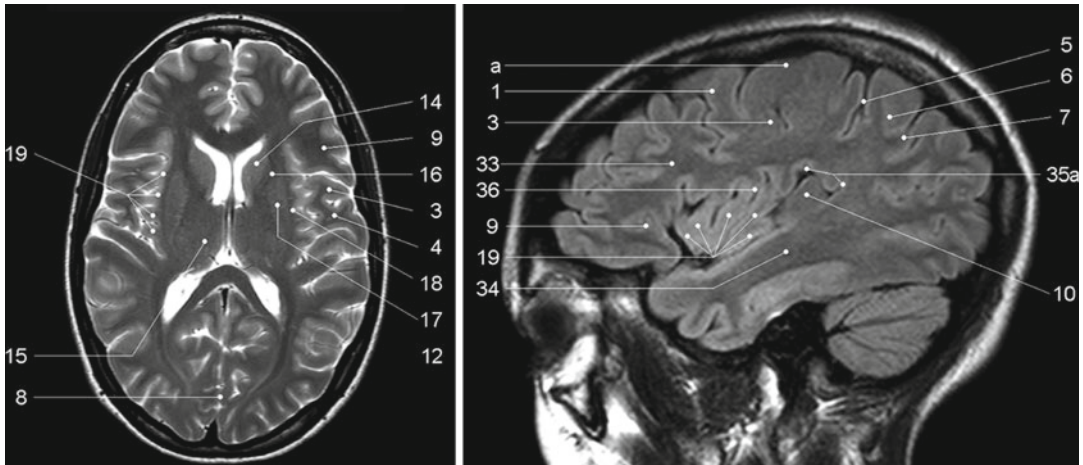
19 insula (anterior and posterior short insular gyri, anterior and posterior long insular gyri), 34 superior temporal gyrus, 35a posterior ascending ramus of the Sylvian fissure, 37 supramarginal gyrus, 38 angular gyrus, 39 pars triangularis, frontal operculum, inferior frontal gyrus, 40 pars orbitalis, frontal operculum, inferior frontal gyrus, 41 medial temporal gyrus

## 2.1.3 Speech-Associated Frontal Areas

### 2.1.3.1 Transverse Sections

In axial sections, the insula [19] can be found easily (see Figs. 2.5 and 2.6). From medial (ventricles) to lateral, the globus pallidus, putamen and

claustrum, within the lentiform nucleus, [17] can be differentiated followed by the extreme capsule [18] and the cortex of the insula [19]. The Sylvian fissure [35b] separates the insula [19] from the temporal lobe. As stated above, the insula – taking anatomic variations into account – has 4–5 knobs



**Fig. 2.6** Axial T2-weighted TSE MR and sagittal FLAIR images. 1 superior frontal gyrus, 3 precentral gyrus, 4 postcentral gyrus, 5 “pars bracket”, cingulate sulcus, 6 precuneus, parietal lobe, 7 intraparietal sulcus, 8 interhemispheric fissure, 9 pars opercularis, inferior frontal lobe, frontal operculum, 10 Heschl’s gyrus, 12 planum temporale, 14 head of the caudate nucleus, 15 thalamus,

16 internal capsule, 17 globus pallidus, putamen, claustrum (lentiform nucleus) 18 extreme capsule, 19 insula (anterior and posterior short insular gyri, anterior and posterior long insular gyri), 33 medial frontal gyrus, 34 superior temporal gyrus, 35a posterior ascending ramus of the Sylvian fissure, 36 central sulcus of the insula

(anterior, medial and posterior short insular gyri divided, by the CS, from the anterior and posterior long insular gyri). The insula [19] is covered by the superior temporal gyrus [34], the frontal operculum [9] and the base of the sensorimotor strip. After identifying the anterior short gyrus of the anterior lobule of the insular cortex, on a transverse view, the anterior border between the insula and inferior frontal lobe is the anterior peri-insular sulcus. It abuts the insula [19], on one hand, and the pars opercularis [9] of the frontal operculum of the inferior frontal gyrus, on the other. The pars opercularis [9] has a triangular shape in axial sections and covers the anterior part of the insula [19]. It can be followed into the anterior cranial fossa where it abuts the gyrus orbitalis that runs parallel to the gyrus rectus. The convolution anterior to the pars opercularis [9] on the lateral surface is the pars triangularis [39], separated by the anterior ascending ramus [35d] of the Sylvian fissure.

### 2.1.3.2 Sagittal Sections

Beginning at the lateral border of the brain (in sagittal views, see Figs. 2.4 and 2.5) there is the Sylvian fissure [35b] that runs anterior-inferior to posterior-superior. Previously, the posterior mar-

gins have been described (see above). The Sylvian fissure separates the temporal lobe from the frontal lobe. At its anterior margin, it ascends into the anterior horizontal ramus [35c] and more dorsally into the anterior ascending ramus [35d] of the frontal operculum [9] that also overhangs the anterior aspect of the insula [19]. The anterior horizontal ramus [35c] separates the pars orbitalis [40] from the pars triangularis [39], whereas the anterior ascending ramus [35d] separates the pars triangularis [39] from the pars opercularis [9] of the frontal operculum of the inferior frontal gyrus that form an “M” (Naidich et al. 1995). The pars opercularis of the frontal operculum of the inferior frontal lobe harbours Broca’s area. At its posterior margin, the pars opercularis is delimited by the anterior subcentral sulcus.

## 2.1.4 Auditory Cortex and Speech-Associated Temporoparietal Areas

### 2.1.4.1 Transverse Sections

From medial to lateral (see Figs. 2.5 and 2.6) towards the insula [19], the globus pallidus,

putamen and claustrum within the lentiform nucleus [17] can be differentiated. Between the lentiform nucleus [17] and the cortex of the insula [19] the extreme capsula [18] is depicted as a small rim of white matter. The Sylvian fissure [35b] separates the insula [19] from the temporal lobe. This is an easy definable landmark on axial views. The insula – taking anatomic variations into account – has 4–5 knobs (anterior, medial and posterior short insular gyri divided, by the CS [36], from the anterior and posterior long insular gyri). Posterior to the convolution that represents the section of the posterior long insular gyrus, a gyrus in the superior temporal lobe can be identified with a dorsomedial to anterior-lateral course, called the transverse temporal gyrus or Heschl's gyrus [10]. This is the primary auditory cortex (Mukamel et al. 2005; Devlin and Poldrack 2007). Number and size may vary (Penhune et al. 1996; Rademacher et al. 2001); however, this is another good landmark that is easy to define. Heschl's gyrus [10] might be interrupted by the sulcus intermedius of Beck. Two gyri on the right and only one on the left hemisphere can be found frequently (Shapleske et al. 1999). Heschl's sulcus [11], which borders Heschl's gyrus [10] posteriorly, is the anterior border of the planum temporale [12]. Although direct cortical stimulation intraoperatively may cause speech disturbances in this area (Sanai et al. 2008; Shapleske et al. 1999), the planum temporale [12] represents, more likely, the auditory association cortex. The planum temporale [12] extends on the superior surface of the temporal lobe and is delimited laterally by the superior temporal sulcus [13], posteriorly by the posterior ascending ramus and/or descending ramus of the Sylvian fissure and medially in the depth of the Sylvian fissure, which is less well defined (Shapleske et al. 1999). These borders are easier depicted in sagittal views; however, in transverse sections, remaining in the same plane in which Heschl's gyrus [10] can be found, the superior temporal sulcus [13] is the next biggest sulcus posterior to Heschl's sulcus [11]. Heschl's gyrus [10] bulges into the Sylvian fissure [35b]. The Sylvian fissure can therefore also be followed in ascending axial images. At the parietotemporal

junction, sulci such as the Sylvian fissure or the superior temporal sulcus [13] ascend, whereas the sulcus intermedius primus descends. This hampers anatomical description in axial sections. Ascending in axial slice order, the superior temporal sulcus [13] diminishes. As Heschl's gyrus [10] bulges into the Sylvian fissure [35b], the Sylvian fissure can be followed on its course as posterior ascending ramus [35a] up to the level of the cella media of the lateral ventricles (in bicommissural orientation), as a big intersection posterior to Heschl's sulcus [11]. The posterior ascending ramus [35a] of the Sylvian fissure is imbedded in the supramarginal gyrus [37] which again is separated from the angular gyrus [38] by the sulcus intermedius primus. Descending in axial slice order, pre- and postcentral gyri can be identified as described above. The next sulcus dorsal to the postcentral sulcus is the intraparietal sulcus [7] which can be followed from the medial apical surface, laterally and dorsally in the parietal lobe [6]. Laterally, it ends above the sulcus intermedius primus and abuts the angular gyrus [38]. Size of the planum temporale [12] varies depending on sex, handedness and hemispherical dominance (Shapleske et al. 1999). Activation in functional imaging studies was found in verb generation tasks (Wise et al. 1991) and listening to tones, words and tone sequences (Binder et al. 1996, 1997, 2000).

#### 2.1.4.2 Sagittal Sections

According to its dorsomedial to anterior-lateral course (see Fig. 2.6), the transverse temporal gyrus or Heschl's gyrus [10] abuts the base of the inferior sensorimotor strip (most likely the postcentral gyrus) at the lateral aspect and the posterior long gyrus of the insula [19] in more medially located sections. It is erected into the Sylvian fissure [35b]. Heschl's sulcus [11], which borders Heschl's gyrus [10] posteriorly, is the anterior border of the planum temporale [12]. The planum temporale [12] extends on the superior surface of the temporal lobe and is delimited laterally by the superior temporal sulcus [13], posteriorly by the posterior ascending ramus and/or descending ramus of the Sylvian fissure and medially in the depth of the Sylvian fissure, which is less well



defined (Shapleske et al. 1999). The Sylvian fissure can be followed from the anterior ascending [35d] and horizontal rami [35c] in the frontal operculum [9] of the inferior frontal gyrus, dorsally to the ascending [35a] and descending rami at the temporoparietal junction. Medially it is flanked by the insula [19], laterally by the superior temporal gyrus [34] and inferior parts of the pre- and postcentral gyri. Parallel to the Sylvian fissure [35b], the superior temporal gyrus [34] also demonstrates an anterior-posterior course. The posterior ascending ramus [35a] of the Sylvian fissure is imbedded in the supramarginal gyrus [37] which has a horseshoe appearance. Posterior to the supramarginal gyrus [37], the superior-inferior running sulcus intermedius primus separates it from the angular gyrus [38]. The superior temporal sulcus [13] ascends at its posterior end and diminishes.

#### 2.1.4.3 Coronal Sections

In coronal views, the Sylvian fissure separating the temporal lobe from the insula and the frontal lobe can easily be seen. Originating from the temporal lobe, Heschl's gyrus points towards the insula (not shown).

### 2.1.5 Visual Cortex

#### 2.1.5.1 Sagittal Sections

At the medial surface of the occipital lobe, there is a sulcus that zigzags anterior-posteriorly called the calcarine sulcus [27], along which the visual cortex is located. The calcarine sulcus [27] separates the superior lip from the inferior lip of the visual cortex.

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