NEUROIMAGING

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modern imaging of its a

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INTRODUCTION

The hippocampus has been a source of fascination from the very origins of neuroscience as a modern discipline. The complexity of this phylogenetically ancient structure, at both the gross and cellular level, has encouraged study by generations of anatomists. Here is a neural landscape, alluring in its intricacy and beauty, not only to the anatomist on histological section, but also to the modern neuroradiologist or neurologist for whom the latest imaging techniques reveal ever more exquisite detail. The appreciation of its role in memory-processing, its association when damaged with complex partial seizures, the refinement of surgical techniques for intractable epilepsy, and the introduction of more powerful imaging modalities will all ensure the continuing importance of the hippocampus in clinical neuroscience.

The term hippocampus (a mythical horse-headed, fish-tailed sea monster, usually translated today as seahorse) was coined by Giulio Cesare Aranzi in Bologna in 1564 (Lewis 1923). He was also the first to describe the temporal horns of the lateral ventricles, and it seems most likely that he was referring to the appearance of the hippocampus from above, after opening the ventricles and removing the overlying choroid plexus, rather than to the appearance on the modern coronal section. Paul Broca made the link between the hippocampus and a number of other structures along the medial surface (edge or limbus) of the cerebral hemisphere in 1878, introducing the term 'limbic lobe' (Broca 1878). The concept of a limbic lobe has been extended since then by James Papez ('Papez circuit' 1937) (Papez 1937), Paul Maclean ('Limbic system' 1952) (MacLean 1952) and others, to furnish a morphological substrate for emotion. The range of neural structures included has grown to include subcortical elements, while recognition of connections with numerous other parts of the brain has proliferated. This lead to the suggestion by Brodal and others that the concept of a discrete 'limbic system' is meaningless and better abandoned (Brodal 1981). Further discussion of this issue is beyond the scope of this article (Kotter & Klaas 1997), and for simplicity we have placed the hippocampus within the traditionally conceived limbic system (Fig. 1).
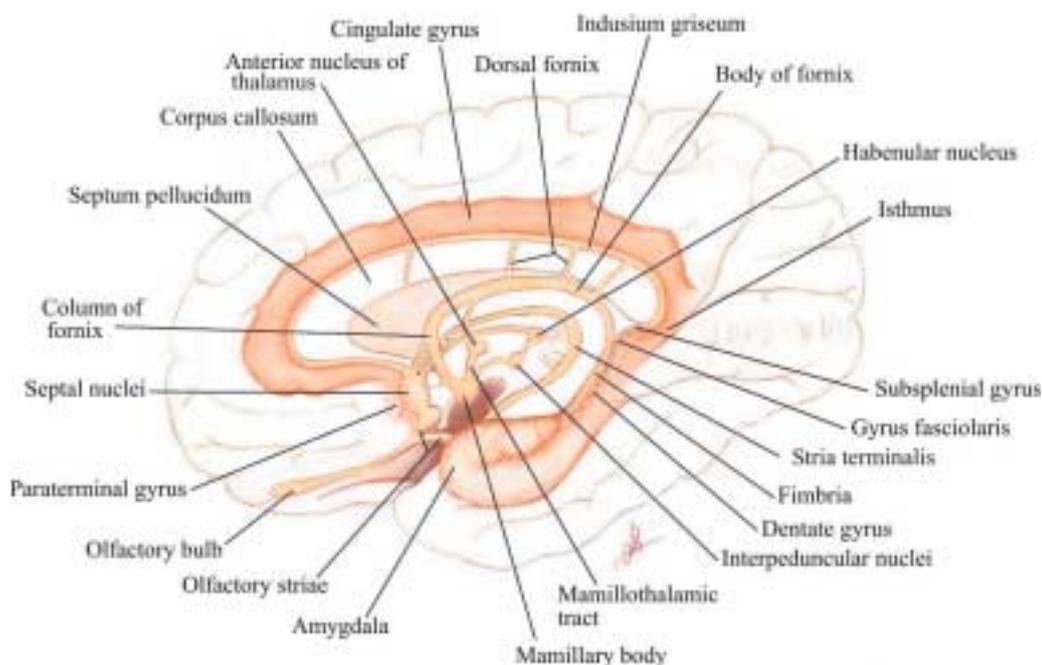
ocampus:
anatomy and pathology

In this article we will review the normal anatomy of the hippocampus as demonstrated by modern MRI, contrasting these normal appearances with several pathological conditions.

HIPPOCAMPAL STRUCTURE

The complex terminology of the hippocampus and adjacent structures can be a barrier to understanding. This becomes even more difficult when different authorities use varying terms for the same structures. We have followed the terminology used in the monographs by Duvernoy (Duvernoy 2005) and Gloor (Gloor 1997) and in other recent articles, using the name hippocampus for the interlocking core structures: Ammon's horn (Cornu Ammonis), and the dentate gyrus (gyrus dentatus). Other authorities [such as Gray's Anatomy (edn Standring 2005)] have tended to reserve the term hippocampus for the Cornu Ammonis alone, distinguishing it from

Figure 1 Components of the limbic system.
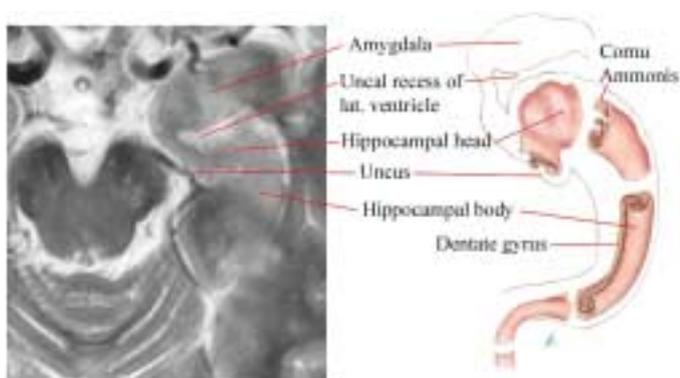
Figure 2 T2-weighted (1.5T) axial image of the left hippocampus shows its resemblance to a seahorse. Note the uncal recess of the temporal horn of the lateral ventricle separating the hippocampal head from the amygdala. The corresponding drawing on the right (based on Duvernoy) shows the interlocking C-shaped Cornu Ammonis and gyrus dentatus of the hippocampus.

the dentate gyrus. Axial MRI shows the location of the hippocampus on the medial aspect of the temporal lobe, in the floor of the temporal horn of the lateral ventricle (Fig. 2).

The bulk of the cerebral cortex consists of isocortex (neocortex), a phylogenetically advanced structure which on microscopy (with Nissl staining) reveals six cell layers. The mesial temporal structures (Fig. 3) are formed of more primitive allocortex with three, four or five layers, and begins development as a flat cortical plate that progressively rolls up to form the interlocking

grey matter, the C-shapes of the Cornu Ammonis and dentate gyrus (Fig. 4).

The fold between the Cornu Ammonis and dentate gyrus is progressively obliterated, leaving only the mouth of the hippocampal sulcus. Frequently vestiges of this sulcus persist as small hippocampal cysts (Fig. 5). White matter fibres from the hippocampus accumulate on the superior surface to form the sheet-like alveus, which is covered by the ependyma of the temporal horn of the lateral ventricle, and overlying choroid plexus (Fig. 5). White matter fibres from the alveus then gather into bundles as the fimbria, which are continuous posteriorly with the fornix. The Cornu Ammonis is continuous inferolaterally with the cortex of the parahippocampal gyrus, specifically the subiculum [which in turn is usually subdivided – see Duvernoy and Gloor (Duvernoy 2005; Gloor 1997)]. From the outside, the hippocampus is largely hidden, only the teeth (dentes) of the dentate gyrus being visible between the fimbria above and the subiculum below (Fig. 3). The parahippocampal gyrus is unique in having a layer of white matter overlying the cortex, the superficial medullary stratum of the subiculum. The transition from allocortex to isocortex is at the lip of the collateral sulcus, modern MRI showing a perceptible thickening of the cortex at this point.

The anterior aspect of the parahippocampal gyrus is known as the entorhinal area, the
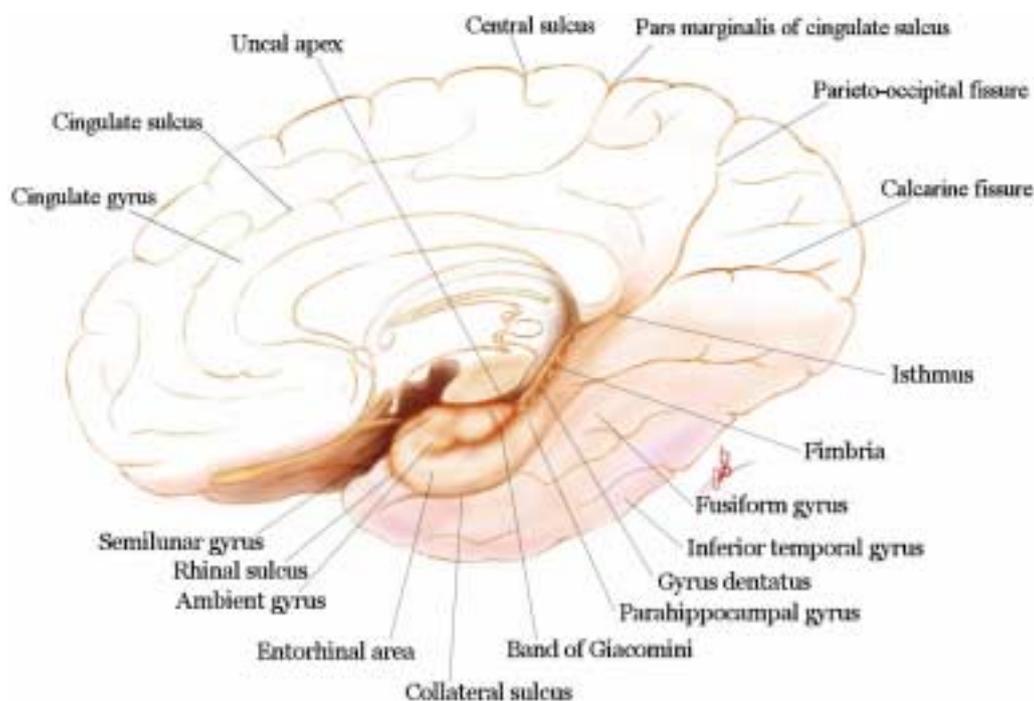
Figure 3 Inferomedial view of the cerebral hemisphere showing the mesial temporal structures. The hippocampus is barely visible externally. Only the 'teeth' of the dentate gyrus are just visible between the fimbria above and the parahippocampal gyrus below.

Figure 4 Internal structure of the hippocampus (see also Fig. 2), showing sections of the body and tail. The Cornu Ammonis is divided into four cellular regions, or fields, designated CA1 (Sommer sector) to CA4. In life, the choroid plexus of the lateral ventricle lies on the alveus. Note the bulge in the floor of the temporal horn of the lateral ventricle produced by the deep collateral sulcus (the collateral eminence). Blue arrow, fimbrio-dentate sulcus; red arrows, hippocampal sulcus.


(a)

(b)

(c)
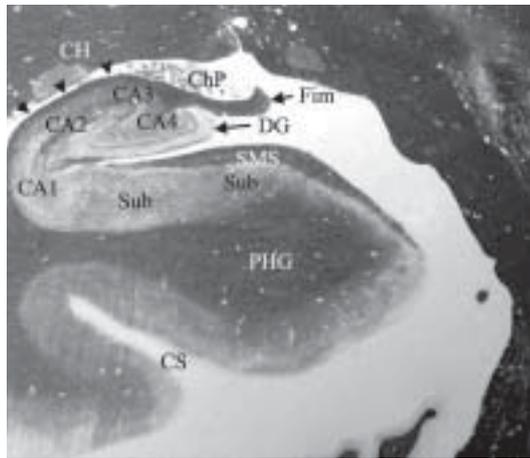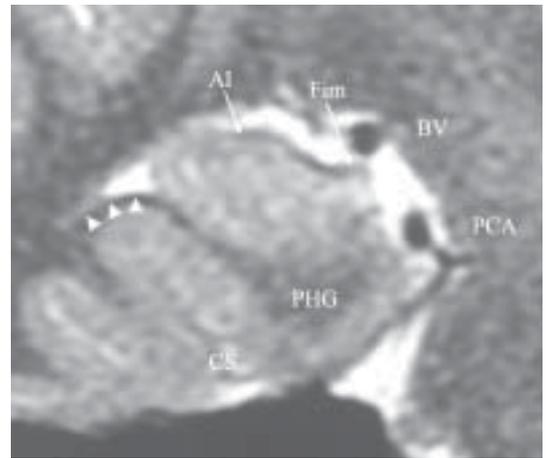
Figure 5 Correlation of histology section (a) Weil (myelin) stain, with coronal T2-weighted MRI at (b) 1.5T and (c) 3.0T. Compare also with Fig. 4. Much detail is visible even on the 1.5T image, while the 3.0T image approaches the low power histology image. Note the thin layer of white matter on the surface of the parahippocampal gyrus: the superficial medullary stratum of the subiculum. A small hippocampal cyst reflects the location of the largely obliterated hippocampal sulcus in (c). CA 1–4 Cornu Ammonis fields, DG dentate gyrus; Sub subiculum; PHG parahippocampal gyrus; Fim fimbria; Al alveus; ChP choroid plexus; CH head of caudate nucleus; SMS superficial medullary stratum of subiculum; CS collateral sulcus; BV basal vein of Rosenthal; PCA posterior cerebral artery; Tent tentorium cerebelli; SCA superior cerebellar artery. In (b) white arrowheads indicate the collateral eminence, the impression on the temporal horn made by this deep collateral sulcus. In (c) black arrowheads: course of obliterated hippocampal sulcus. White arrowhead: hippocampal cyst.
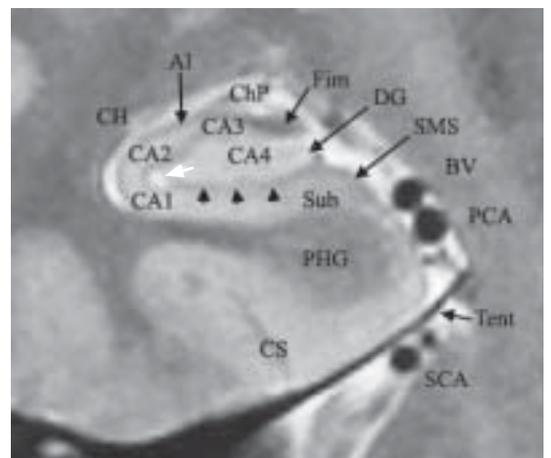
principle source of input to the hippocampus. Posteriorly, in the hippocampal tail, the inferomedial aspect of the Cornu Ammonis produces several bulges, the gyri of Andreas Retzius, below the fasciola cinerea, the posterior extent of the dentate gyrus (Fig. 4). In the hippocampal tail the Cornu Ammonis also emerges below the fimbria as the gyrus fasciolaris, which continues posteriorly around the splenium of the corpus callosum to become the thin sheet of overlying grey matter known as the indusium griseum.

IMAGING THE HIPPOCAMPUS

The current generation of 1.5T MR scanners give detailed images of the hippocampal region and, with the introduction of higher field MRI units, some of the internal structure of the hippocampus is becoming discernable. These developments necessitate greater familiarity with the anatomy in all three orthogonal planes. T2-weighted images have generally proved most useful although signal change within the hippocampus may be more easily confirmed on FLAIR or proton density images. T1-weighted images may allow better grey-white matter dis-crimination and aid in identifying coexisting cortical dysplasias and heterotopias.

The axial plane (Fig. 6) gives a useful overview of the temporal lobe and may reveal gross lesions or variations. Unless the possibility of temporal lobe pathology or epilepsy has been raised clinically, coronal studies are unlikely to have been performed, and the axial image may therefore give the only clue to a lesion. Good quality axial images may thus prompt further coronal imaging.

Coronal T2-weighted MRI has long been the mainstay of temporal lobe imaging. Reading the images form anterior to posterior allows detailed analysis of all parts of the hippocampus, and most usefully, comparison with the other side. It is important to begin reading anteriorly at the temporal poles to check for symmetry in positioning of the patient – otherwise spurious differences in the size of the hippocampi may be encountered. Behind the temporal pole, the first mesial temporal structure is the large rounded grey matter mass of the amygdala, after which the hippocampal head body and tail are progressively revealed (Fig. 7). The hippocampal tail is usually not so
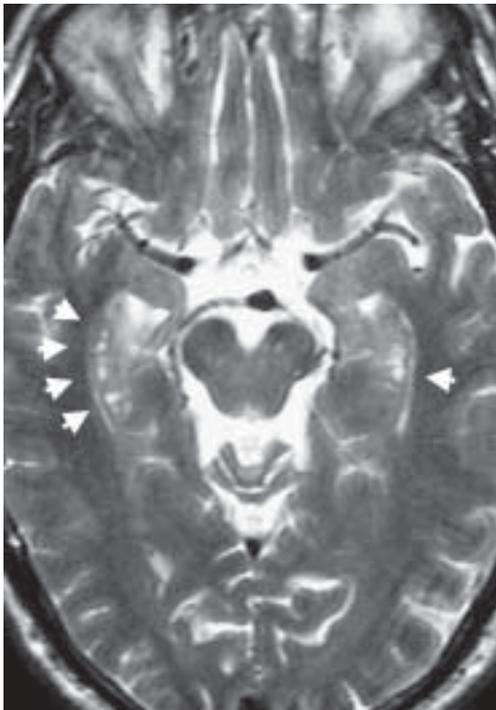
Figure 6 Axial T2-weighted image (1.5T). A series of small incidental hippocampal cysts (white arrowheads) indicate the line of the fused hippocampal sulcus but are of no clinical significance.
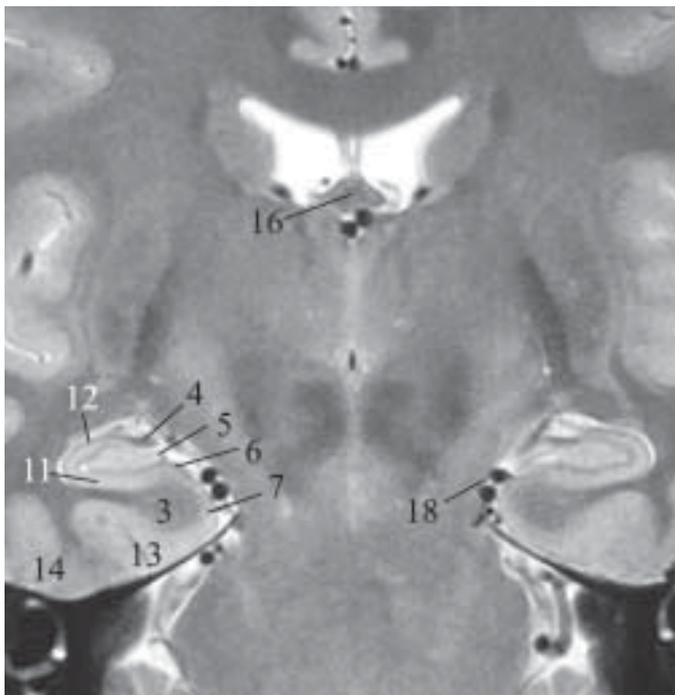
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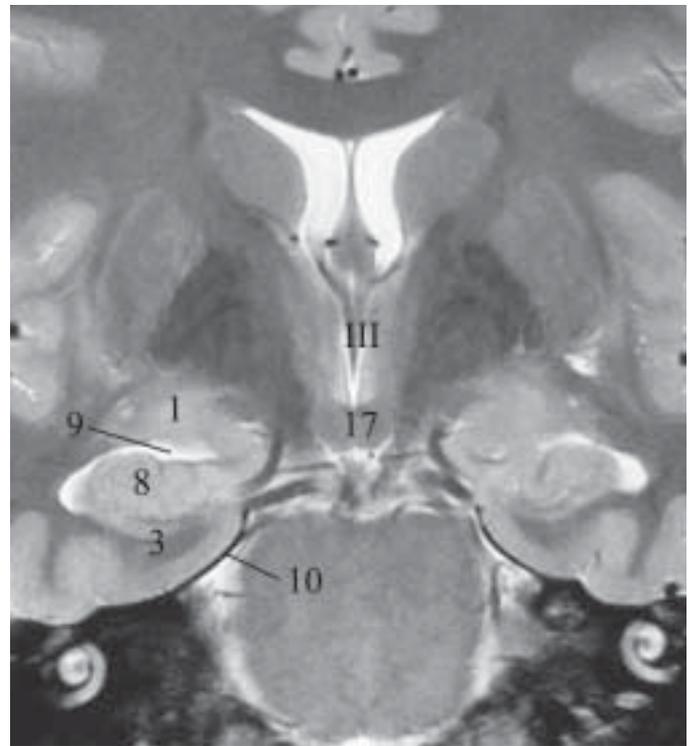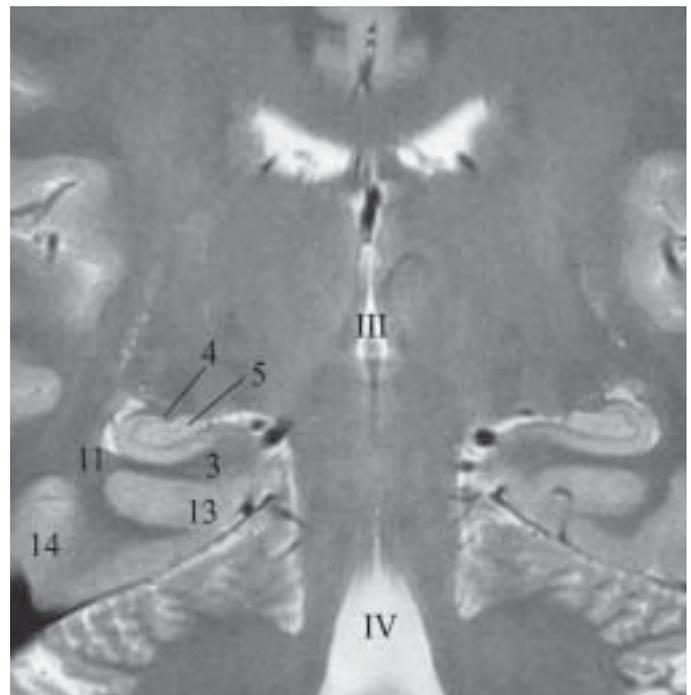
Figure 7 Coronal T2-weighted (3.0T) MR images of normal hippocampus from anterior (a) to posterior (d). Compare with Fig. 4. 1 amygdala, 2 uncus, 3 parahippocampal gyrus, 4 fimbria, 5 dentate gyrus, 6 subiculum, 7 entorhinal area, 8 hippocampal head (note digitations), 9 uncal recess of temporal horn, 10 free margin of tentorium, 11 Cornu Ammonis, 12 alveus, 13 collateral sulcus, 14 fusiform (medial occipitotemporal sulcus), 15 anterior commissure, 16 fornix, 17 mamillary bodies, 18 vessels in ambient cistern medial to choroid fissure (basal vein superior, posterior cerebral artery inferior), III 3rd ventricle, IV 4th ventricle.
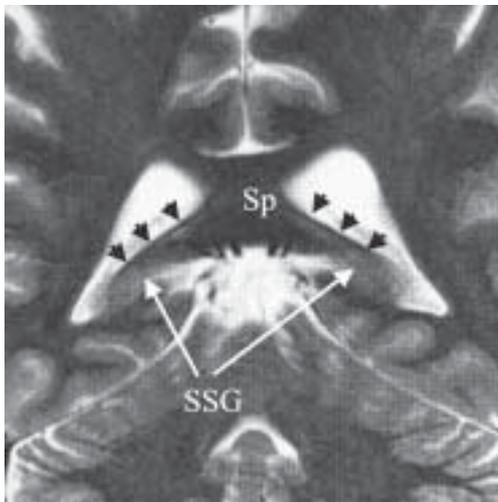
Figure 8 Coronal T2-weighted (1.5T) image of the hippocampal tail showing the crura of the fornix (black arrowheads) slanting supero-medially from the hippocampus to join the splenium (Sp) of the corpus callosum, and the subsplenial gyri (SSG) of the hippocampal tail.

clearly distinguished although with practise the subsplenial gyri can be discerned (Fig. 8). The columns of the fornix are readily identified. Even with 3.0T images, we cannot reliably identify the indusium griseum on the surface of the corpus callosum

Sagittal images of the hippocampus are becoming particularly useful on modern highfield MRI. The whole extent of the hippocampus is revealed and pathology can now be assessed directly without reference to the contralateral side (except for size comparison) (Fig. 9).

Coronal imaging however, most readily depicts hippocampal lesions, in particular hippocampal (or mesial temporal) sclerosis (Fig. 10).

Of course, in the investigation of complex partial seizures, especially if surgery is contemplated, MRI findings must be correlated with other investigations including EEG, and often SPECT or PET as well. Attempts at identifying the degree of contribution of the ipsilateral hippocampus to memory processing, prior to temporal lobectomy, are usually made by performing a Wada test (Wada 1949). This involves performing a cerebral catheter angiogram and then injecting sodium amytal into the internal carotid artery (ICA) producing temporary anaesthesia of the portion of the cerebral hemisphere supplied by the ICA. Tests of short-term memory can then be performed.
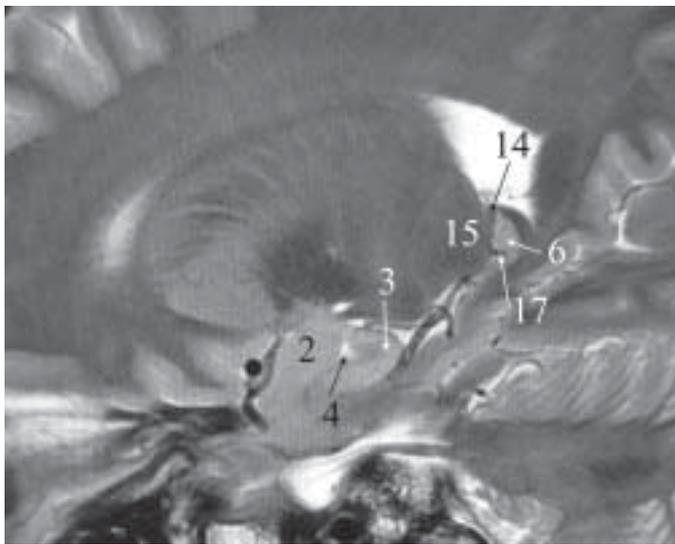
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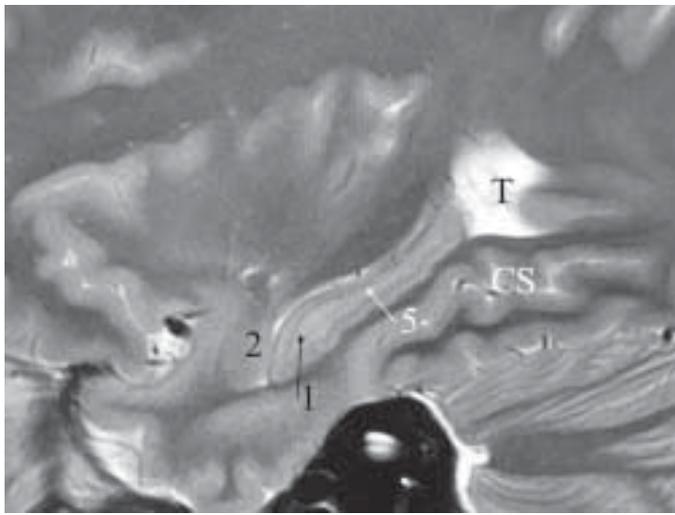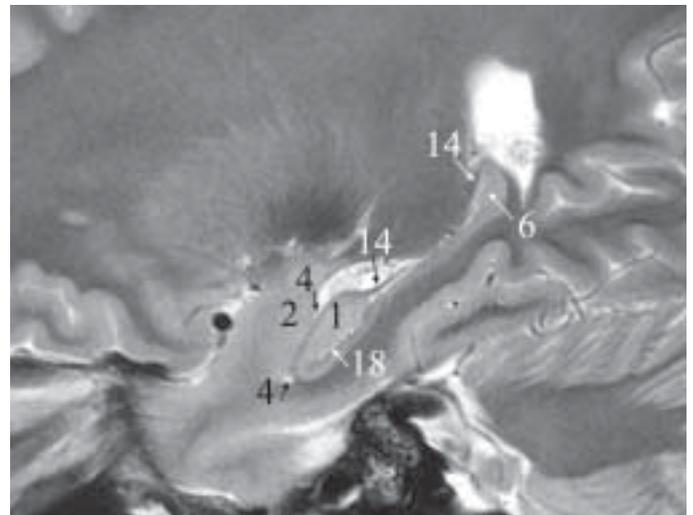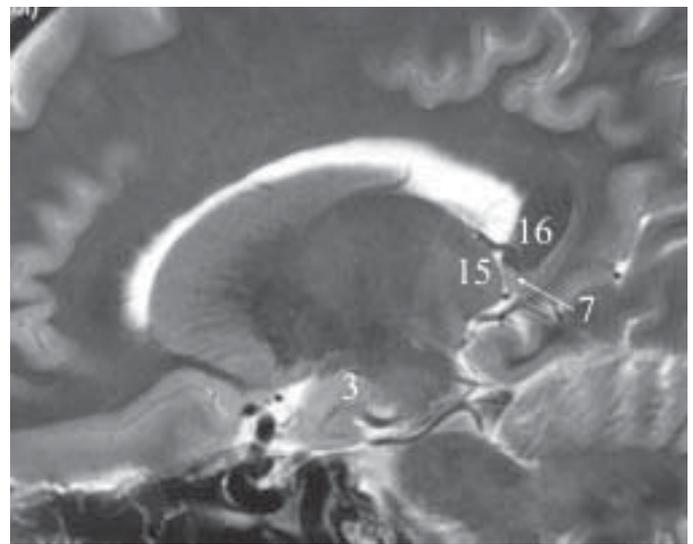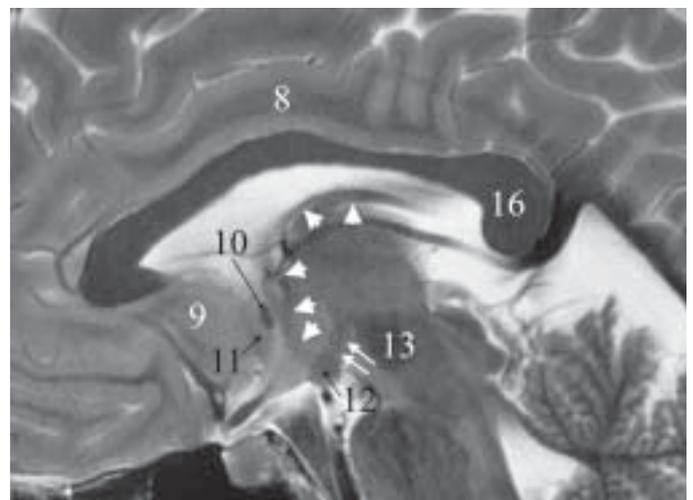
Figure 9 Sagittal T2-weighted (3.0T) MR images of normal hippocampus from lateral (a) to medial (e). 1, hippocampal head; 2, amygdala; 3, uncal pole; 4, uncal recess of temporal horn; 5, hippocampal body; 6, hippocampal tail; 7, subsplenial gyrus; 8, cingulate gyrus; 9, septal area; 10, anterior commissure; 11, paraterminal gyrus; 12, mamillary body; 13, mamillothalamic tract; 14, fimbria; 15, pulvinar of thalamus; 16, splenium of corpus callosum; 17, anterior choroidal artery; 18, hippocampal sulcus. T, trigone of lateral ventricle; CS collateral sulcus; white arrowheads, fornix.

(a)　　　　(b)
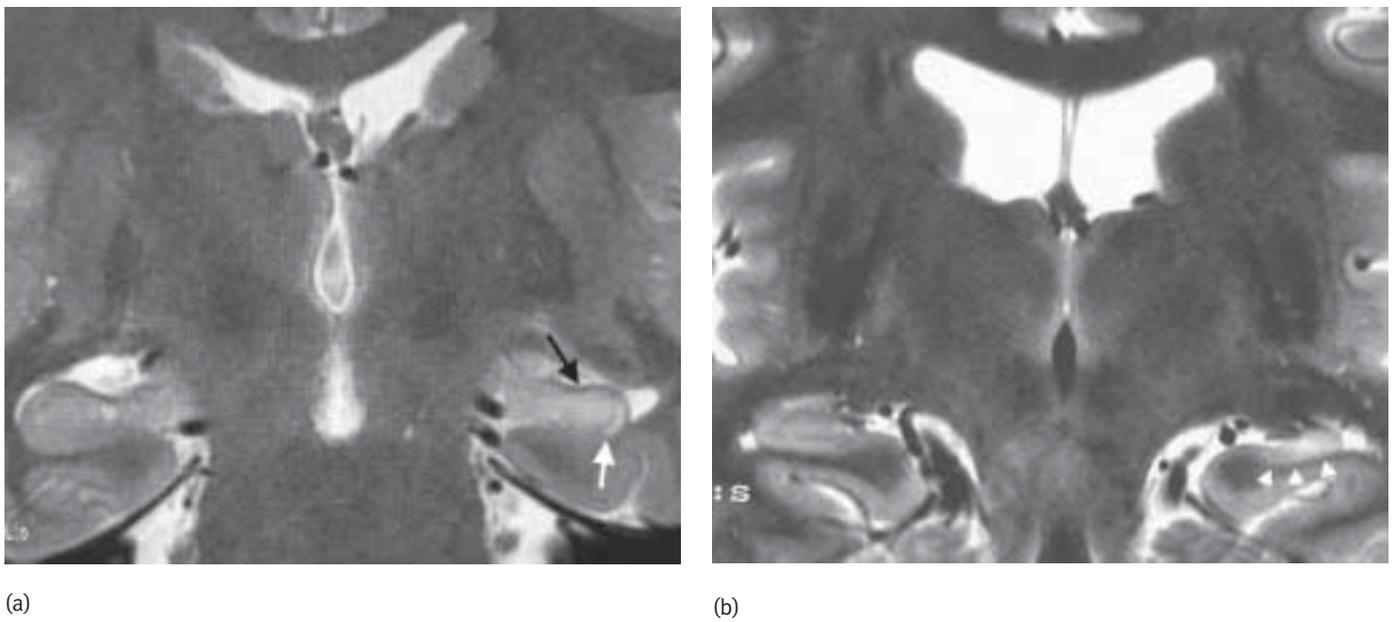
Figure 10 (a) Coronal T2-weighted MRI (1.5T) of a 42-year-old woman with poorly controlled complex partial seizures. The left hippocampus is smaller than the right and shows high-signal change typical of mesial temporal sclerosis. This emphasizes the entire extent of the alveus as a dark surface stripe (black arrow). Note that the high signal of the hippocampus terminates abruptly at the medial border of the CA1 field (white arrow), with no extension into the subiculum. (b) In this patient with MTS note the medial extension of the high signal change into the subiculum (white arrowheads).
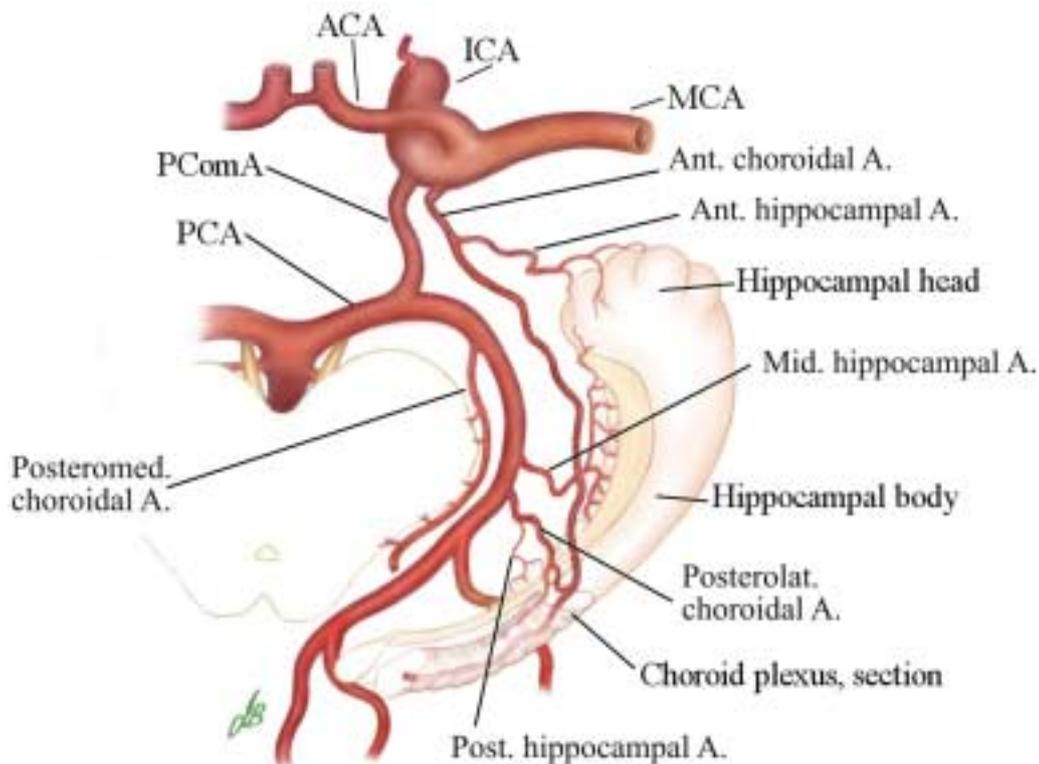
Figure 11 Blood supply to the hippocampal region is quite variable. The main supply to the hippocampus usually arises from the posterior circulation via single or multiple middle and posterior hippocampal arteries. ACA, anterior cerebral artery; ICA, internal carotid artery; MCA, middle cerebral artery; PcomA, posterior communicating artery; PCA, posterior cerebral artery; A, artery.
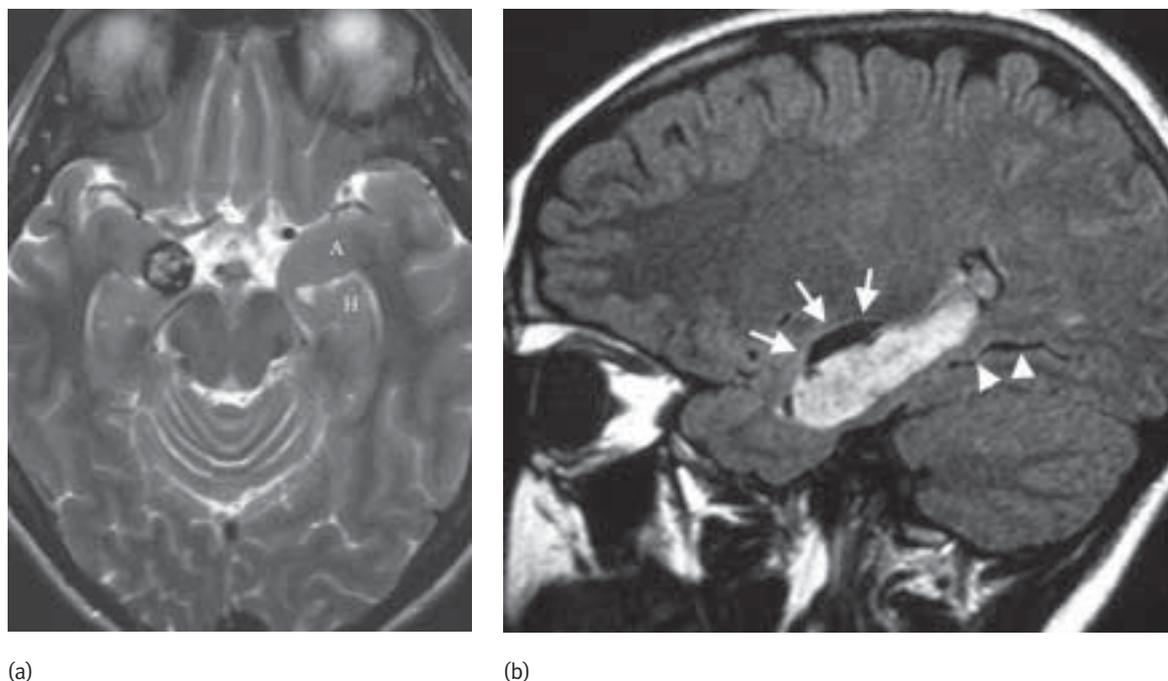
Figure 12 MRI images 1.5T of hippocampal pathology. (a) Axial T2 image showing a cavernous malformation, with its typical black ring of haemosiderin, located in the uncus on the right, straddling the medial aspect of the amygdala and hippocampal head. A: left amygdala, B: left hippocampus, separated by uncal recess of temporal horn. (b) Sagittal T2 FLAIR image showing the entire left hippocampus to be enlarged and of abnormal uniform high signal; this proved to be a low grade astrocytoma. The temporal horn is dilated and obstructed (white arrows). The collateral sulcus is visible posterior to the lesion (arrowheads).

The results should be interpreted with caution however: the internal carotid artery usually only contributes to the blood supply of the hippocampal head via the anterior choroidal artery. Most of the blood supply arises from the posterior cerebral and postero-lateral choroidal arteries (Duvernoy 2005; Jack *et al.* 1988) derived from the vertebrobasilar system (Fig. 11).

Imaging of the temporal lobes in epileptic (or indeed asymptomatic) patients although often normal, may reveal numerous other lesions (Fig. 12).

CONCLUSIONS

Modern MRI units (1.5T or 3.0T) reveal the structure of the hippocampal region in ever greater detail. However, this does require greater familiarity with temporal lobe anatomy in all three orthogonal planes. Rather than simply identifying the hippocampus as normal or abnormal, involvement of specific segments of the hippocampus is now possible. This offers the tantalizing possibility (as yet unrealized) of correlating structural abnormalities within the hippocampus with variations in seizure semiology.

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