査によれば、新生児聴覚スクリーニングで「リファー」となった赤ちゃんを詳しく検査した結果、約60%が正常でした。

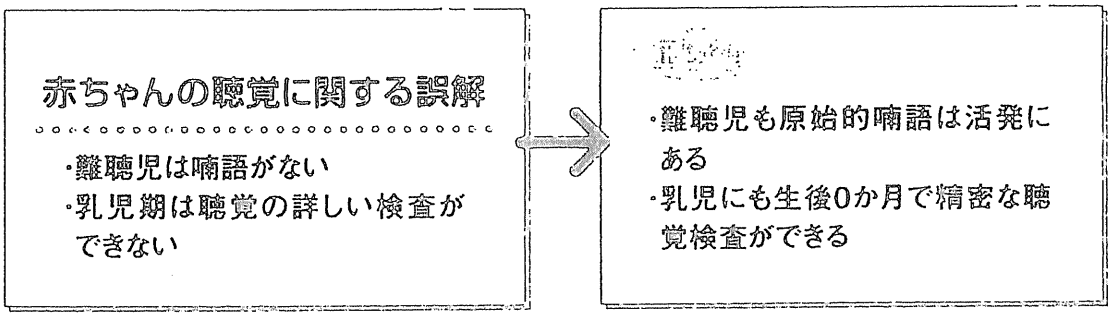
専門的な検査のできる病院を受診する

―― では、スクリーニングで「リファー」と言われたら、親はどうすればいいですか。

加我　日本耳鼻咽喉科学会が「精密聴力検査機関」として全国の160余りの施設を指定しています。ホームページ（URL:http://www.jibika.or.jp/mimiyori/sinseiji_list.html）に掲載していますので、このリストにある最寄りの病院を受診してください。そこでは次のステップとして、さらに詳しい検査をします。基本はABR（聴性脳幹反応）ですが、自動ABRよりも精度の高い装置を使って専門家が詳しく検査して、正確に難聴の重さや脳幹の発達を評価しますから、聴力にどの程度の問題があるかがわかります。加えて、行動反応聴力検査といって、目が覚めている状態で音に対する身体反応を調べます。音の大きさを変えて反応を調べ、もっとも小さな値を「閾値」として目安にする検査です。この2つが必須ですが、耳音響反射聴力検査などを加えることもあります。これらの検査はいずれも長所と短所があるので、そのことを考慮に入れていくつもの厳密な検査を重ねて、総合的に判断します。また、成長とともに改善したり、悪化したりすることがあるので、注意深く経過観察をして確定診断をするのです。

―― 大きな病院に行く前に、かかりつけの小児科や耳鼻咽喉科で、精密検査の時期などについて相談する親ごさんもいるのではないでしょうか。

加我　そういう場合もあるでしょう。しかし、なるべく早く、専門の医師がいる大きな病院を受診していただくのがベストでしょう。というのも、ひと口に耳鼻咽喉科の先生といっても、必ずしも耳や聴覚が専門とは限らない。難聴に詳しくない先生もいるし、とくに乳幼児の難聴について詳しい医師は極めて少ないのが現状です。「しばらく様子をみましょう」と言われて発見が遅れ、大事な時期を逃してしまうことも少なくありません。また、小児科や保健所で行われている乳幼児健診では、「この月齢で聴覚の詳



しい検査はできない」とか「喃語があるから大丈夫」などの誤解から「半年後にもう一度来てください」と言われてしまう場合もあります。難聴に正しい知識がないために、正常なのに聴覚障害があると言われたり、障害の発見が遅れて療育の機会を逃してしまったり。こうしたことを避けるために、大きな病院の耳鼻咽喉科を受診することを勧めたいのです。

――「喃語があるから大丈夫」は誤解なのですか。つまり、聴覚障害児にも喃語がある?

加我　ありますよ。喃語には、生後2～3か月頃までの原始的喃語と、ことばを話し始める前の標準的喃語の2種類があるのですが、原始的喃語は先天性難聴の赤ちゃんにも活発にあります。しかし、それを知らない医者や保健師もいて、乳幼児健診などで誤った判断をしてしまう場合があります。

生後6か月までに補聴器をつけて教育を始める

――では、精密検査は急いで受けたほうがいいですか。

加我　「異常がある」と言われた親ごさんは気が気でないはずです。検査は早く受けたほうがいいでしょう。精密聴力検査の結果、ほんとうに聴力に問題があるとわかれば、生後6か月までに補聴器を装用して音を聞かせる教育を始めます。

――生後6か月で? それはどんな教育ですか。

加我　「教育」というのは保育園や幼稚園と同様のものですが、難聴児の場合はたくさん音を聞かせて遊ばせる。つまり、砂遊びや積み木ではなくて音の出るおもちゃや

教材を使って遊ばせる……そういう教育をするのです。アメリカの調査によれば、生後6か月までに補聴器を装用して教育を開始した子を3歳の時点で評価すると、健常児の約90%の言語力を持つといわれます。しかし1歳以降に同じ教育を始めても、3歳で7～8割の言語力にしかたどり着かないというデータです。このアメリカの報告が世界中に影響を与えて、日本にも導入された経緯があります。

どんな治療・療育がある?

◉障害の程度により選択肢はさまざま
補聴器、人工内耳、言語聴覚療法、音楽療法、手話…etc
※その子の状況に応じてさまざまな分野から検討して方針を決める

◉日常的な働きかけが重要
赤ちゃんの頃から話しかけたり笑いかけるなど、豊富なコミュニケーションが発育・発達によい影響を与える
※聞こえないからと放っておいてはいけない

―― どこで教育を受けるのですか。

加我　教育施設には、①難聴児通園施設、②地域の身障センター・療育センター、③ろう学校の3つの種類があります。どこも、最初は補聴器をつけて教育を始めますが、重い難聴がある子は、1歳半以降に人工内耳の手術を受けて、耳で聞いて話す教育(聴覚口話法教育)を受けるという道があります(表2)。

―― 補聴器ではダメな場合もあるということですか?

加我　ええ。難聴が極めて重く、補聴器の効果が乏しい子がいるんです。そういう子は2歳前後を目安に人工内耳の手術をします。ここは国内でもっとも多く幼小児の人工内耳の手術を手掛けている病院のひとつですが、人工内耳をつけて適切な教育を受けた子は小学校に上がる頃にはほとんど健常児と変わりなく、よく聞いてよく話すことができます。しかし、補聴器の場合は難聴児特有の発音になりやすい。また、通っ

表2　就学前の教育施設

難聴児通園施設	全国に27	児童福祉法によるもので、厚生労働省管轄
地域の身障センター・療育センター	全国に多数	地域の地方自治体管轄
ろう学校	全国に102	学校教育法によるもので、文部科学省管轄 ※私立、国立、都道府県立、市立などの種類があります。

た教育施設によって、聴覚口話法教育で「聞いて話す」教育を徹底して行うところと、手話を併用しているところとがあり、聞いて話す力に差が出てきます。というのも、手話を併用すると手話のほうが便利なので、そちらにエネルギーが傾くのです。すると、子どもたちはことばを話さなくなりがちなのです。

―― では、重い難聴がある子は人工内耳をつけるのが望ましいわけですね。

加我　私たちのグループのように、「聞いて話せる」力を身につけさせたいと考える医者や言語聴覚士は人工内耳を勧めますが、手話を主体にしようと考える人たちもいます。聴覚障害児の教育法は親の価値観によって大きく左右されるのです。

―― たとえば、親ごさんにも聴覚障害があって手話ができないと親子のコミュニケーションが成立しない、などという場合ですか。

加我　そういう方もいますが少数です。手話というのは250年の歴史を持つ、伝統的なコミュニケーション法で、これを選択しようと考える健常者の親ごさんもいるのです。

聴覚障害児の早期発見を

―― 「聞いて話せる子」に育てたいときは、難聴の程度にかかわらず人工内耳をつけたほうがいいのですか。

加我　補聴器をつければ、よく聞こえて話せるという場合は、人工内耳の手術はしません。その判断は言語聴覚士と耳鼻咽喉科の医師が行います。

―― 全国的には、まだまだ新生児聴覚スクリーニングが行われていない地域も多いようです。検査を受けていない赤ちゃんで聴覚に不安があるようなとき、親はどうすればいいですか。また、そういう相談を受けた母子保健の専門職はどう対応すればいいですか。

加我　繰り返すようですが、ただちに専門的な検査のできる病院を受診するのがいいでしょう。母子保健の専門職は、地域の専門病院を挙げて、「ここで検査を受けてください」と伝えてほしいと思います。近くにない場合、インターネットで調べて地方から私のところを受診する方も少なくありません。

―― 最後に改めて、聴覚障害児を早期発見する大切さを整理してください。

加我　まず、早期に正しい診断をして、生後6か月までに補聴器を装用して音を耳に入れてあげることが重要です。音の刺激によって、眠っていた脳の聴覚システムが働き始めるからです。そして、障害の程度によって医学的な対応や療育の方針について方向性を見極めます。それに沿って、適切な時期に、さまざまな分野の専門家が関わって対応していくことが重要です。聴覚口話法による「聞いて話す」教育を受けるのか、補聴器と手話の併用でいくのか、補聴器や人工内耳を選択するか、手話だけにするのかの判断も2歳前後が大きな転機です。脳の発達には可塑性があり、やり直すことができません。だから、人工内耳の手術も遅くとも5歳までにはしてあげたい。これは脳の発達と競争のようなところがあり、5歳以降になると効果が遅れたり少なくなってしまう可能性があるからです。しかし、重い難聴があっても早期に発見し、補聴器や人工内耳をつけて適切な教育を受けた子は高校や大学への進学率も高い。この事実を多くの方たちに、正しく知っていただきたいと思います。

加我 君孝 先生
プロフィール

東京大学医学部医学科卒業。東大病院研修医、帝京大学医学部耳鼻咽喉科学教室助手、講師、助教授を経て、米国ジェファーソン医科大学の医学教育・医療研究所、UCLA脳研究所に留学。1992～2000年東京大学耳鼻咽喉学教授、2000～2007年東京大学医学教育国際協力研究センター長。2007年より現職。主な研究分野は、聴覚認知、両耳聴、脳と言語・音楽、聴性脳幹反応の臨床応用、乳幼児の難聴バランス機能の発達、言語の神経科学。

The Auditory System

7

Hans J. ten Donkelaar and Kimitaka Kaga

Contents

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7.1 Introduction

The ear or vestibulocochlear organ is composed of external, middle and inner parts (Fig. 7.1). The external ear consists of the auricle and the external acoustic meatus with the outer layer of the tympanic membrane. The middle ear is formed by the tympanic cavity, the auditory ossicles and the inner layer of the tympanic membrane. The inner ear comprises the labyrinth, a series of fluid-filled spaces in the petrous part of the temporal bone. The auditory part of the inner ear consists of the cochlea with the organ of Corti, which contains hair cells as auditory receptors. Receptors sensitive to high frequencies are located near the cochlear base and those sensitive to low frequencies near the apex of the cochlea. The hair cells are innervated by the peripheral processes of bipolar ganglion cells in the spiral ganglion. Their central processes form the cochlear division of the vestibulocochlear nerve and terminate in the cochlear nuclei. The principal auditory pathway passes from the cochlea, via the cochlear nuclei, the inferior colliculus and the medial geniculate body (MGB) to the contralateral auditory cortex on the dorsal surface of the superior temporal gyrus. Each MGB is bilaterally innervated, so that each hemisphere receives cochlear input bilaterally. All of the components of the auditory pathway are tonotopically organized.

At birth, humans have about 20,000 inner and outer hair cells in the organ of Corti, which often do not last a lifetime as they do not regenerate when lost (Stone et al. 1998). By the age of 65–75 years, many individuals have a bilateral, high-frequency progressive hearing loss known as presbycusis associated with hair cell attrition. Hair cell loss is the most common cochlear defect causing hearing impairment in presbycusis and noise-induced hearing loss. Hearing disorders due to brain stem lesions are rare because of the bilateral projections of the central auditory pathways. Midline pontine lesions may result in impaired sound localization due to interruption of the input of the superior olivary complex (see Sect. 7.3.2 and ***Clinical case 7.2***). Disorders of

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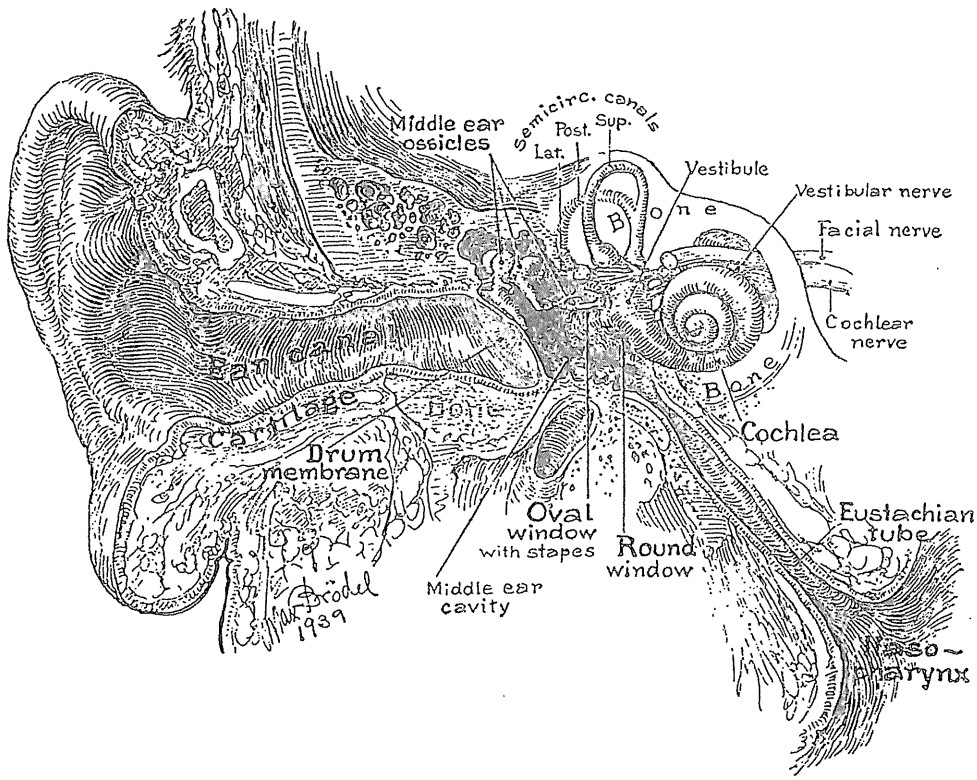


Fig. 7.1 Overview of the external, middle and internal ear (from Brödel 1946)

auditory perception may follow strokes in the territory of the internal carotid arteries or of the vertebrobasilar system. The central disorders of auditory perception may result from lesions of either the right and the left or both cerebral hemispheres, usually involving parietotemporal cortical areas as illustrated in *Clinical cases* (see Sect. 7.4.4).

7.2 The Cochlea and the Cochlear Nerve

7.2.1 The Middle Ear and the Cochlea: Mechanical Transmission of Sound

The **middle ear** comprises the tympanic cavity, the tympanic membrane, the three auditory ossicles, two middle ear muscles, air-filled cavities formed by the mastoid antrum and mastoid air cells, and the auditory tube. The **tympanic cavity** communicates with these air-filled cavities and through the auditory tube with the nasopharynx (Fig. 7.1). The three **auditory ossicles** are the hammer or **malleus**, the anvil or **incus** and the stirrup or **stapes**. The head of the malleus is anchored to the tympanic membrane, whereas the base of the stapes is connected to the fenestra vestibuli or oval window. Sound waves set the tympanic membrane into vibrating movements, which via the auditory ossicles are transmitted to the inner ear. The **inner ear** or cochlea is a fluid-filled tube that is coiled two and a half times. In cross-section, it has a broad base, a pointed apex and a central pillar called the modiolus. The osseous labyrinth communicates with the tympanic cavity through two openings in its medial wall, the oval window or **fenestra vestibuli** and the round window or **fenestra cochleae**. The oval window is closed by the base of the stapes, so that vibrations of the auditory ossicles are transmitted to the perilymph of the inner ear.

Motion of the auditory ossicles is modified by two small **middle ear muscles**, the tensor tympani and the stapedius. The **tensor tympani** is the largest of the two. It is attached to the handle of the malleus and is innervated by the trigeminal nerve. The smaller **stapedius** attaches anteriorly to the head of the stapes and is innervated by the facial nerve. The stapedius and tensor tympani motoneurons form separate cell groups, situated close to the facial and motor trigeminal nuclei, respectively (Lyon 1978; Mizuno et al. 1982; Shaw and Baker 1983). The stapedius functions to protect the auditory receptors of the inner ear against excessive stimulation caused by too strong sound pressure. The sound pressure depends on the amplitude of the waves: the greater the amplitude, the higher the sound pressure. The stapedius contracts in response to sounds above 70 dB (the intensity of loud conversation), damping the movements of the auditory ossicle chain. The tensor tympani contracts to louder sounds, especially impulse noises. The **acoustic middle ear reflex** includes projections from the ventral cochlear nucleus via the superior olivary nuclear complex to the motor nuclei of the trigeminal and facial nerves (Borg 1973). With electro-acoustic impedance measurements, **stapedius muscle contraction** can be readily detected in response to ipsilateral or contralateral sound, giving objective information

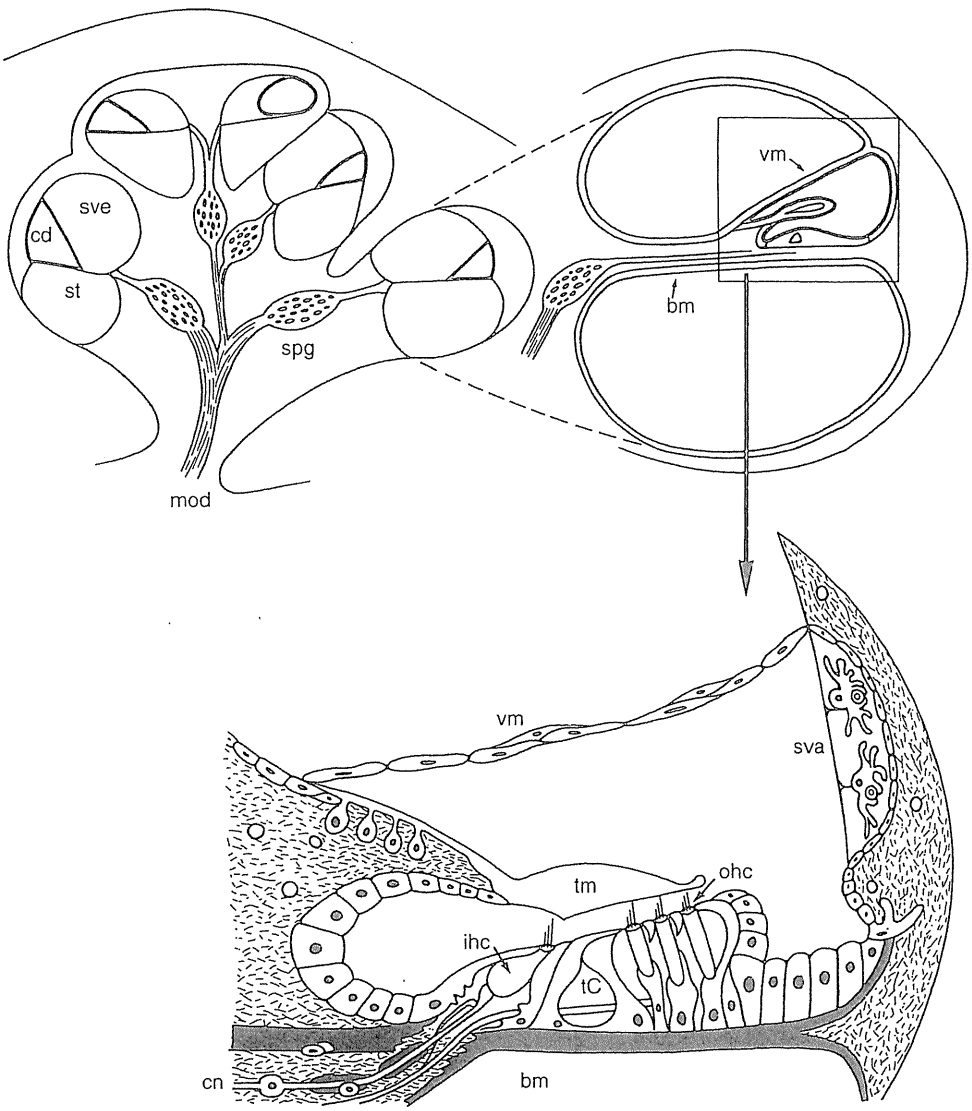


Fig. 7.2 The foetal cochlear duct. At 16 weeks of development, the cochlear nerve (*cn*) fibres pass through a central pillar, the modiolus (*mod*), whereas their cells of origin form the spiral ganglia (*spg*). Below, details of the spiral organ are shown for 25 weeks of development. *Abbreviations*: *bm* basilar membrane; *cd* cochlear duct; *ihc*, *ohc* inner and outer hair cells; *st* scala tympani; *sva* stria vascularis; *sve* scala vestibuli; *tC* tunnel of Corti; *tm* tectorial membrane; *vm* vestibular (Reissner) membrane (from ten Donkelaar et al. 2006)

about the functional state of the middle and the inner ear, the auditory and facial nerves and the central auditory pathways in the lower brain stem. Ipsilateral and contralateral measurements can distinguish between right, left and midline lesions of the lower brain stem (Hayes and Jerger 1981).

The **cochlea** is composed of three chambers or scalae: the scala vestibuli, the scala media and the scala tympani, separated from each other by the vestibular membrane of Reissner and the basilar membrane (Fig. 7.2). The inner scala media is filled with endolymph, which is rich in potassium and has the character of intracellular fluid. The perilymph of the outer scalae vestibuli and tympani has approximately the same composition as the cerebrospinal fluid. The two perilymph compartments form one space, since they are continuous with each other at the apex of the cochlea (the helicotrema). The perilymph drains to the subarachnoid space. The **scala media** or **cochlear duct** contains the organ of Corti, which rests on the basilar membrane (Fig. 7.3). The superior wall of the cochlear duct (the membrane of Reissner) angles downwards from lateral to medial, making the cochlear duct wedge shaped. The lateral wall is the stria vascularis. The thickened epithelium that constitutes the **organ of Corti** can be divided into hair cells and supporting cells. The hair cells are the sensory receptor cells of which there is a single row of inner hair cells and three rows of outer hair cells. The supporting cells include the inner and outer pillar cells, which are separated by the tunnel of Corti extending the length of the cochlea. Both the hair cells and the supporting cells are overlaid by the gelatinous tectorial membrane. In humans, there are 12,000 outer hair cells in three rows at the basal turn, increasing to four to five rows in the second and apical turns, and 3,500 inner hair cells in a single row (Retzius 1884; Bredberg 1968; Kimura 1975). On their apical side, the hair cells contain contractile proteins, including an actin cuticular plate, and about 100 stereocilia, graded in length, which extend to the overlying tectorial membrane. The stereocilia

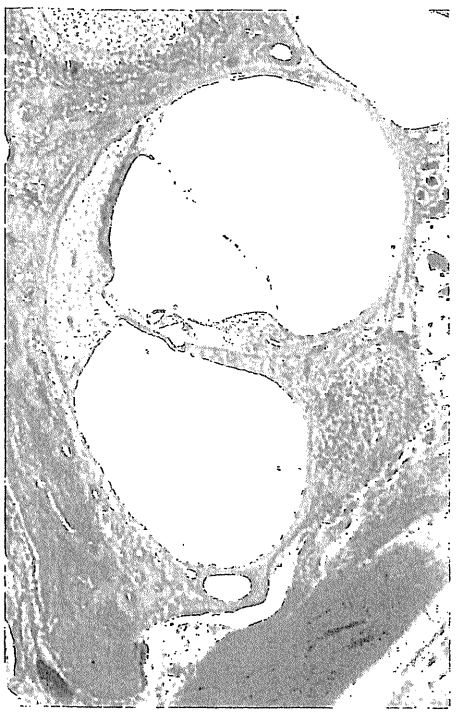


Fig. 7.3 Photomicrograph of the human cochlea (from ten Donkelaar et al. 2006; courtesy Jo Curfs, Nijmegen)

are composed of the active contractile proteins actin and myosin (Flock 1980; Corwin and Warchol 1991). The afferent fibres from the hair cells pass from the organ of Corti through small openings in the osseous lamina into the modiolus. Their cell bodies are located in the modiolus in Rosenthal's canal as the spiral cochlear ganglion (Sect. 7.2.3). The inner ear is vascularized by the **internal auditory artery** which in some 80% is a branch of the anterior inferior cerebellar artery (Kim et al. 1990; Schuknecht 1993).

7.2.2 Cochlear Hair Cells: Transduction and Amplification

The human ear can detect sound waves with frequencies between 20 and 20,000 cycles per second or Hertz (Hz), i.e. approximately ten octaves of sound. The human ear has the greater sensitivity for sounds around 1,000 Hz. The greater the frequency, the higher the pitch. The sound vibrations that enter the scala vestibuli and the perilymph at the oval window produce displacement of the basilar membrane before they finally dissipate back to the middle ear by movements of the membrane covering the round window. **Transduction** of **sound** occurs in the sensory cells of the organ of Corti. Oscillations of the basilar membrane produce a shearing force on the stereocilia of the receptor cells, which are in firm contact with the non-oscillating tectorial membrane. The tilting of the stiff cilia is the adequate stimulus for the auditory receptor cells. The inner and outer hair cells have different roles in the transduction of energy within the cochlea. Inner hair cells provide direct input to almost all of the axons in the cochlear nerve. Their activity is modified by local **amplification** of the motion of the basilar membrane produced by the outer hair cells and hair-cell related supporting cells (Flock et al. 1999; Moore and Linthicum 2004). Several molecules have been identified as having a vital role in hair-cell transduction. They are specifically expressed in and around the stereocilia and mutations in their genes lead to deafness (Steel and Kros 2001; ten Donkelaar et al. 2006).

7.2.3 Spiral Ganglion Cells and the Cochlear Nerve: Neural Transmission

The transition from hair cell activity to neural activity occurs within the cochlea. Activation of the stereocilia results in changes in the intracellular potential that lead to the release of a neurotransmitter from synaptic vesicle clusters at the base of the hair cells. Opposite such a cluster of synaptic vesicles, bulbous nerve terminals are found on the outer surface of the cell wall. Six to eight such terminals are present on the base of each inner hair cell, and a smaller number on each outer hair cell (Nadol 1990). These terminals continue as short unmyelinated processes, forming the "dendritic" segment of cochlear nerve fibres. They become myelinated when they enter the osseous spiral lamina. Here, they reach their cells of origin, the **spiral ganglion cells**. The **spiral ganglion** extends only halfway from the base of the cochlea to the apex. Therefore, the peripheral processes, containing hair cells in the apical and middle turns of the cochlea, extend down through the modiolus to reach the most apical ganglion cells. In humans, there are about 35,000 spiral ganglion cells (Hinojosa et al. 1985; Spoendlin 1985). Two types of ganglion cells are found (Spoendlin 1985). The majority (90–95%) are type I cells and contact inner hair cells. The unmyelinated peripheral processes of the remaining ganglion cells (5–10%), the type II cells, contact the outer hair cells. The central processes of both types of ganglion cells form the cochlear nerve (Spoendlin and Schrott 1989). The **cochlear nerve** enters the ventral cochlear nucleus on the ventrolateral side of the inferior cerebellar peduncle (see Fig. 7.6a). Upon entering the brain stem, primary auditory fibres bifurcate into equally sized ascending and descending branches (Moore and Osen 1979).

7.2.4 The Auditory Periphery: Generation of Evoked Activity

Neural activity is reflected in the **brain stem auditory-evoked potentials** or **responses** (**BAEPS** or **BAERs**), an externally recordable series of small amplitude and short latency wave-like potentials evoked by a transient stimulus

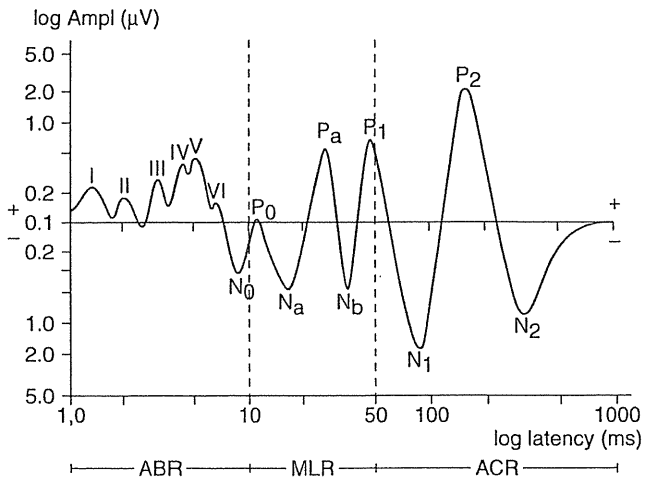


Fig. 7.4 Brain stem (ABR), middle latency (MLR) and cortical (ACR) auditory-evoked responses (from Pasman 1997; courtesy Jaco Pasman, Nijmegen)

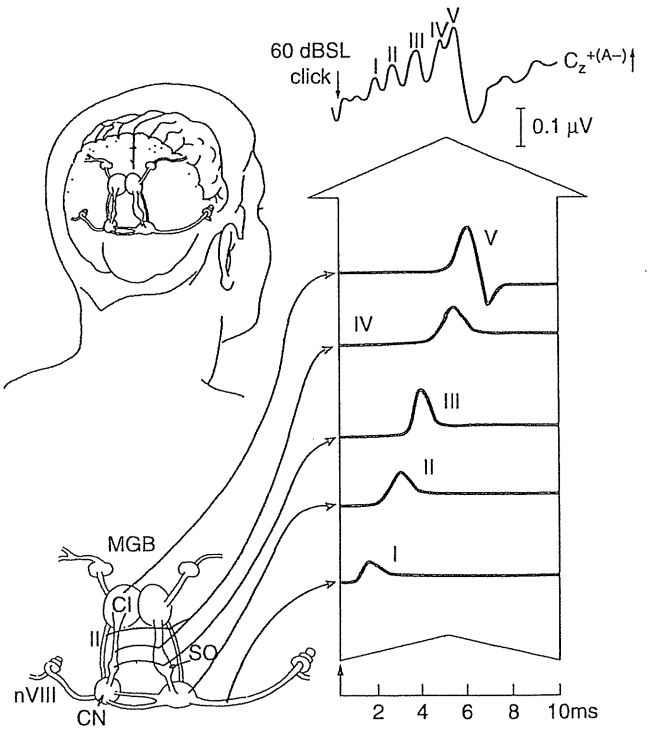


Fig. 7.5 Relationship between components of the brain stem-auditory evoked response and the auditory projection pathway. *Abbreviations*: *CI* colliculus inferior; *CN* cochlear nuclei; *ll* lateral lemniscus; *MGB* medial geniculate body; *nVIII* vestibulocochlear nerve; *SO* superior olive; *I–V* waves of BAEP (after Stockard et al. 1978)

such as a click (Jewett et al. 1970; Stockard et al. 1978, 1986). Auditory-evoked responses (AERs) can be subdivided according to their latency into brain stem (ABR), middle latency (MLR) and cortical (ACR) AERs (Fig. 7.4). In humans, the ABR or BAEP is characterized by six or sometimes seven deflections (I–VII) in the first 9 ms after the stimulus. Waves I, III and V are of greatest interest since they reflect volume-conducted activity from the levels of the acoustic nerve, pons and midbrain, respectively. The earliest BAEP waves (waves I and II) are generated by the cochlear nerve, prior to its entrance into the brain stem (Stockard et al. 1978, 1986; Moller and Jannetta 1982; Martin et al. 1995; Fig. 7.5). A potential corresponding to wave II of the scalp-recorded BAEP can be recorded intrasurgically from the surface of the human cochlear nerve as it passes through the internal auditory meatus and crosses the intradural space (Martin et al. 1995). This supports an earlier dipole localization study (Scherg and von Cramon 1985). Therefore, both waves I and II of the human BAEPs are generated by activity in axons of the cochlear nerve. BAEPs can distinguish between pathologies of the middle and inner ear, the auditory nerve and the brain stem. There are three major applications of BAEPs in adults: (1) the detection of tumours in the region of the posterior cranial fossa; (2) evolution of coma; and (3) assessment of patients with suspected demyelinating diseases such as MS. Acoustic neurinomas may cause complete loss of wave I on the side of the lesion or a significant increase in the I to III interpeak latency.

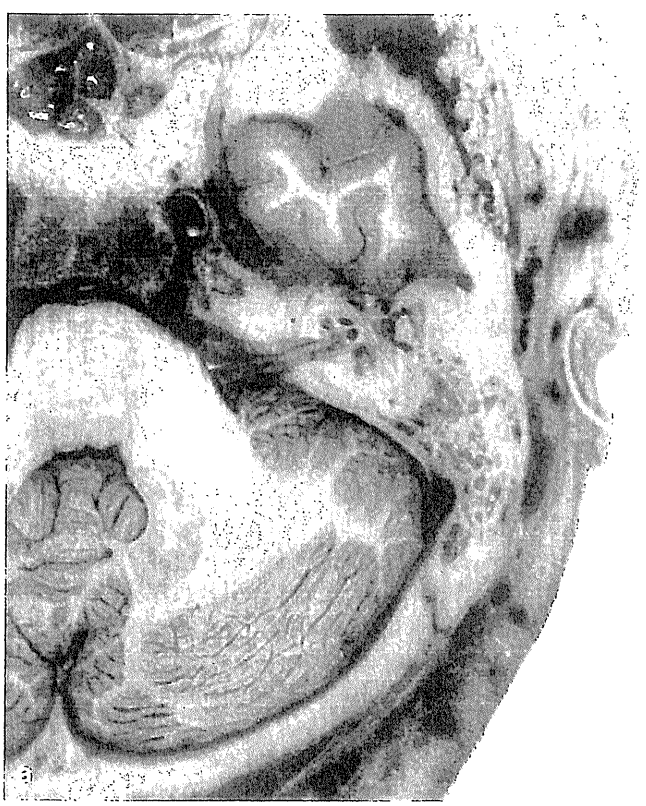
7.2.5 Hearing Loss

Two types of hearing loss can be distinguished: conductive and sensorineural. ***Conductive hearing loss*** is related to defects in conductive mechanisms in the middle ear, resulting from conditions such as otitis media and otosclerosis. ***Sensorineural hearing loss*** is caused by disease in the cochlea or its central connection, the cochlear nerve. Hearing loss of cochlear origin is common and can result from a variety of conditions, including tumours, infections, temporal bone fractures or from exposure to excessive noise or ototoxic drugs (Schuknecht 1993). In ***presbycusis***, the hearing loss of the aged, the loss begins with degeneration of outer hair cells at the basal end of the cochlea, but does not seriously affect hearing until the upper range of speech frequencies, around 3,000 Hz, is affected. Noise-induced hearing loss and severe blows to the head tend to affect the anterior basal turn of the cochlea, the region that processes 3,000–4,000 Hz (Moore and Linthicum 2004). ***Tinnitus***, characterized by noise in the ears such as ringing, humming or whistling, is a common symptom in disorders of the inner ear, but it can also occur in disorders affecting the VIIIth nerve such as an ***acoustic neurinoma*** (see ***Clinical case 7.1***) and with vertebrobasilar disease. Sudden onset of unilateral or bilateral deafness usually accompanied by dizziness or vertigo can be a sign of occlusion of the basilar artery (Huang et al. 1993; Levine and Häusler 2001).

Clinical Case 7.1 Cerebellopontine Angle Tumour

Electrocochleography and auditory brain stem response (ABR) are important electrophysiological tools for routine use in diagnosing vestibular schwannomas (Eggermont et al. 1980; Chandrasekhar et al. 1995). Kaga et al. (1997) reported a case of a vestibular schwannoma in which electrocochleography and ABR were correlated with temporal bone pathology (Fig. 7.6).

Case report: A 74-year-old female presented with a left hearing impairment. In 1975, she had undergone mastectomy of her left breast and in 1987, at the age of 73, she was treated with cobalt radiotherapy for a recurrence of the breast cancer. Pure tone audiometry revealed threshold elevation in the middle- and high-frequency range. ABR showed no response in the left ear but electrocochleography showed clear compound action potentials. CT scanning and MRI demonstrated the presence of a medium-sized cerebellopontine angle tumour in the left ear (Fig. 7.7a, b). Three years later, she died of metastatic lung cancer and sepsis. At autopsy, metastases of the breast cancer were found in the right upper lobe of the lung and in the right temporal lobe of the brain. The temporal bone pathology consisted primarily of a large schwannoma, originating from the left inferior vestibular nerve and occupying the left internal auditory meatus (Fig. 7.7c, d). The organ of Corti was well preserved in each turn. In the modiolus, the numbers of spiral ganglion cells and cochlear nerve fibres in each turn were decreased. These histological findings suggest that clear compound action potentials were recorded from the distal part of the cochlear nerve in spite of the presence of the vestibular schwannoma. ABR could not be detected because of the blockade of the proximal portion of the cochlear nerve by the vestibular schwannoma.



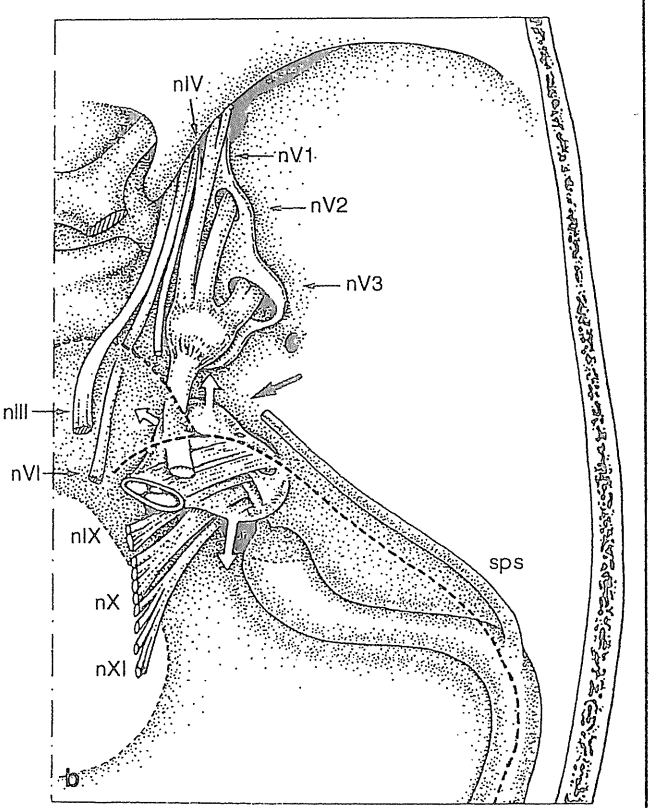


Fig. 7.6 (**a**) The course of the vestibulocochlear nerve from the inner ear to the brain stem on the right and (**b**) the cerebellopontine angle. The *black arrow* in (**b**) points at an acoustic neurinoma and the way it extends (*white arrows*). *Abbreviations*: *nIII* oculomotor nerve; *nIV* trochlear nerve; *nV1* ophthalmic nerve; *nV2* maxillary nerve; *nV3* mandibular nerve; *nVI* abducens nerve; *nIX* glossopharyngeal nerve; *nX* vagal nerve; *nXI* accessory nerve; *sps* superior petrosal sinus ((**b**) after ten Donkelaar et al. 2007)

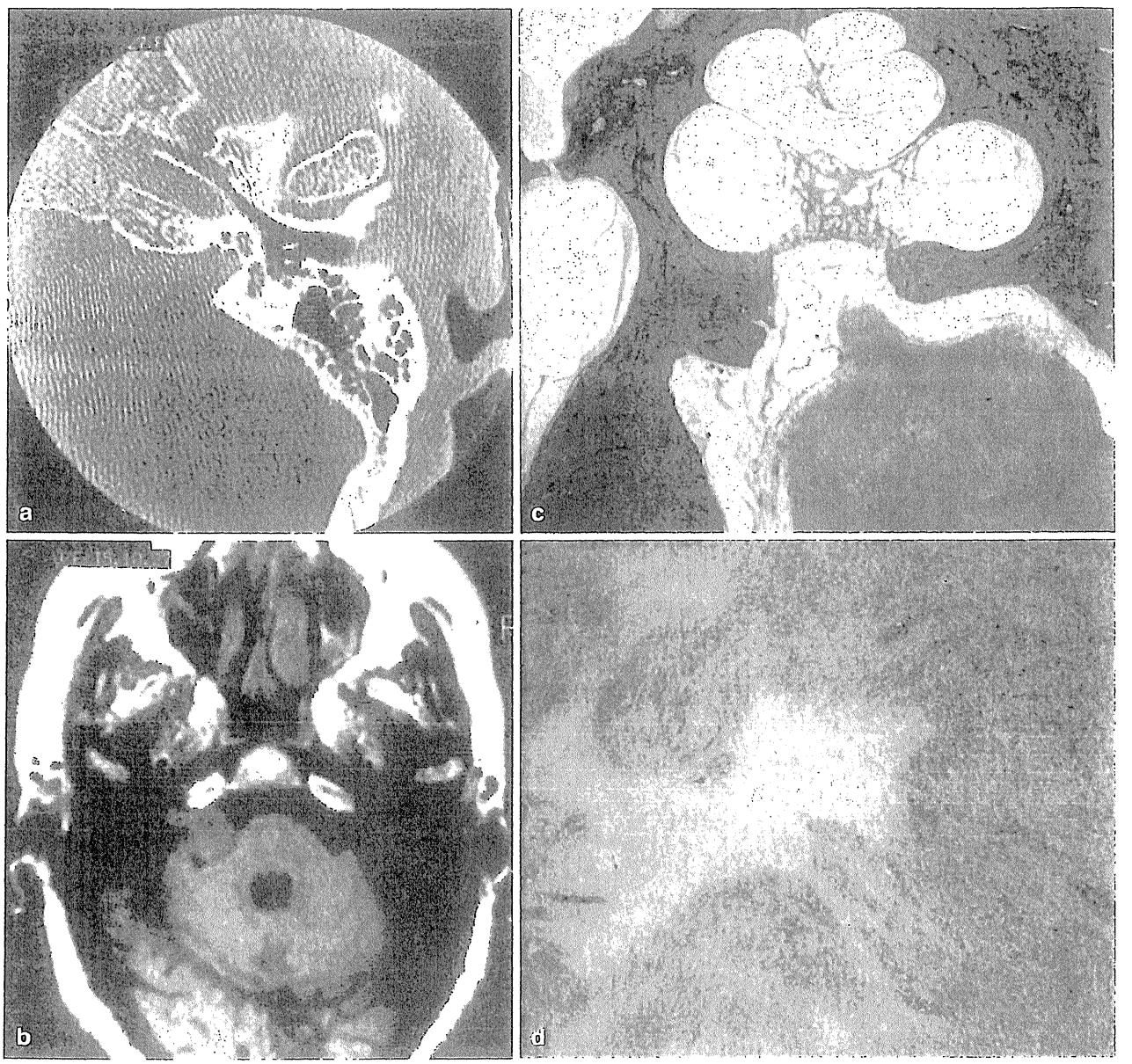


Fig. 7.7 (**a, b**) CT and MRI demonstrating the presence of a medium-sized tumour in the left internal auditory canal and the cerebellopontine angle. (**c**) Mid-modiolar section of the left ear showing enlargement of the internal auditory canal occupied by a vestibular schwannoma (HE stain). (**d**) Magnification of the vestibular schwannoma with mixed Antoni A and B cell types (HE stain; from Kaga et al. 1997)

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7.3 The Brain Stem Auditory System

Upon entering the brain stem, the central processes of the spiral ganglion cells bifurcate and distribute to the cells of the dorsal and ventral cochlear nuclei (Sect. 7.3.1). The organization of the terminations was first described by Lorente de Nó (1933), based on his Golgi studies in a 4-day-old cat. In squirrel monkeys, fibres from the basal turn of the cochlea project to dorsal regions of the ventral cochlear nucleus, whereas apical fibres project to ventral regions (Moskowitz and Liu 1972). The primary cochlear nuclei contribute bilateral ascending projections to the superior olivary complex and to the lateral lemniscus (Sect. 7.3.2). The majority of the lateral lemniscal fibres ascend directly to the inferior colliculus (Sect. 7.3.3). Ascending projections from the inferior colliculus form the brachium of the inferior colliculus and reach the MGB (Sect. 7.4.1), which via the acoustic radiation (Sect. 7.4.2) projects to the auditory cortex (Sect. 7.4.3).

7.3.1 The Cochlear Nuclei: Diversification of Cochlear Input

The human cochlear nuclei consist of a large ventral nucleus and a smaller dorsal nucleus (Moore and Osen 1979; Terr and Edgerton 1985; Adams 1986). The **dorsal cochlear nucleus** contains a large variety of cell types, and is situated dorsolateral to the inferior cerebellar peduncle. The **ventral cochlear nucleus** contains many different cell types and has anteroventral, ventral and posteroventral subnuclei, which borders are not well defined, however. The cochlear nuclei receive a rich **blood supply** from multiple sources, including branches of the anterior and posterior inferior cerebellar arteries (Oas and Baloh 1992).

The **secondary auditory projections** from the cochlear nuclei to the superior olivary complex and the inferior colliculus take various routes (Fig. 7.8). Ipsilaterally, a major projection from both ventral and dorsal cochlear nuclei reaches the superior olivary complex (Sect. 7.3.2). Contralaterally, there are three major ascending cochlear projections (Strominger 1973; Strominger et al. 1977): (1) the largest originates in the ventral part of the ventral cochlear nucleus and forms the **trapezoid body**; its axons may proceed directly to the contralateral lemniscus or terminate in the superior olivary complex; (2) fibres from the dorsal part of the ventral cochlear nucleus form the **intermediate acoustic stria**; they contribute to the lateral lemniscus; and (3) a contralateral projection from the dorsal cochlear nucleus, forming the **dorsal acoustic stria**. The dorsal and intermediate acoustic striae and the trapezoid body converge to form the **lateral lemniscus**. The auditory nuclei do not only serve as relay nuclei in the ascending auditory projection, but also as reflex centres. Efferents from the cochlear nuclei enter the reticular formation, where they contact neurons of the

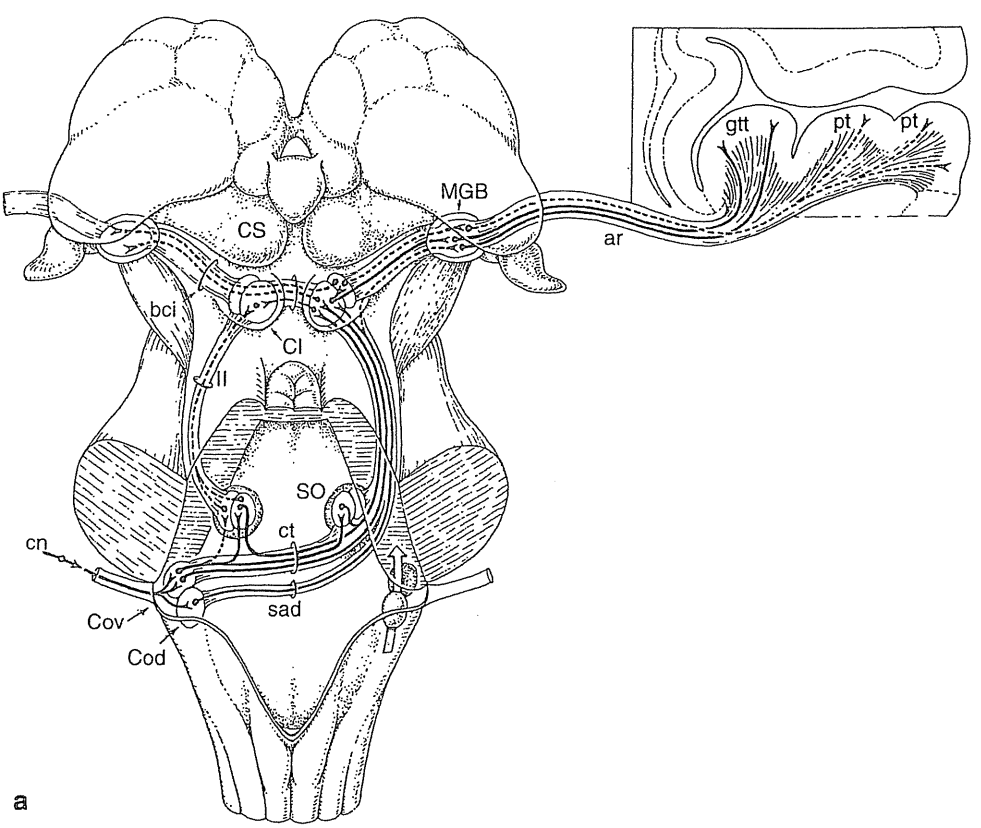

Fig. 7.8 (**a**) Overview of the auditory projections in the human brain (after ten Donkelaar et al. 2007); (**b–d**) the position of the cochlear nuclei (in *red*), the lateral lemniscus (in *light red*) and the colliculus inferior (in *red*) in horizontal sections of the brain stem (after Duvernoy 1995). *Abbreviations*: *ar* acoustic radiation; *bci* brachium of colliculus inferior; *CI* colliculus inferior; *cn* cochlear nerve; *Cod, Cov* dorsal and ventral cochlear nuclei; *CS* colliculus superior; *ct* corpus trapezoideum; *gtt* gyrus temporalis transversus (Heschl's gyrus); *ll* lateral lemniscus; *MGB* medial geniculate body; *pt* planum temporale; *sad* stria acoustica dorsalis; *SO* superior olive

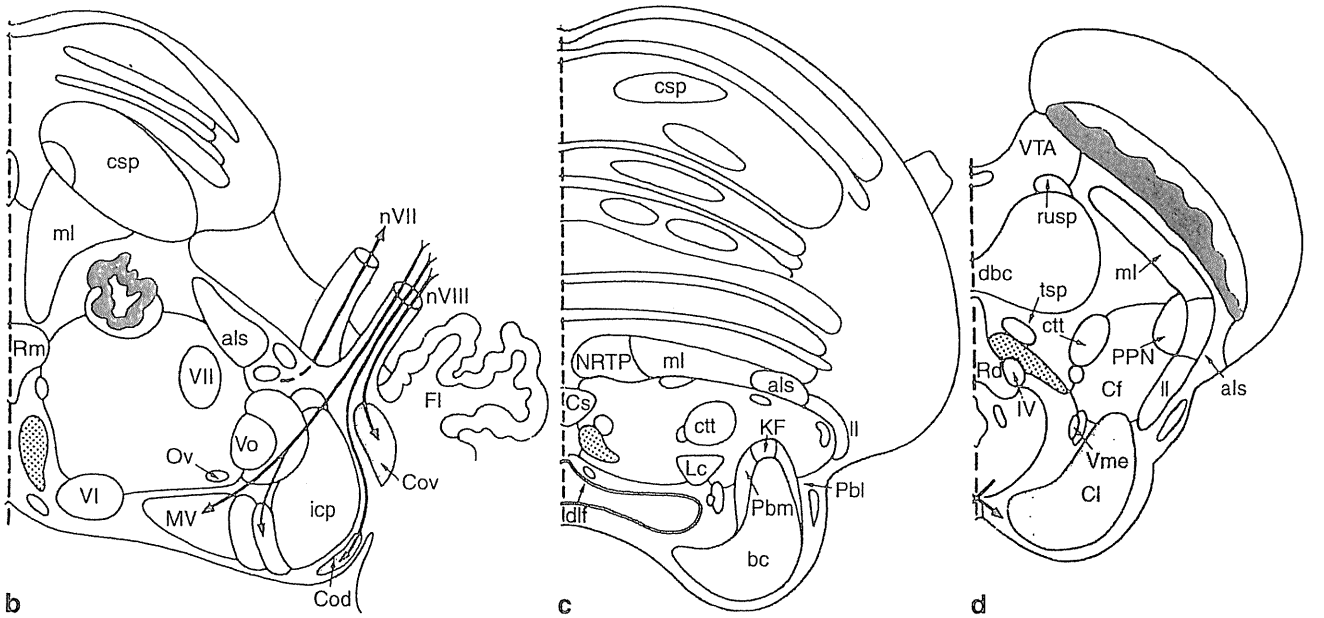

Fig. 7.8 (continued)

ascending reticular activating system (see Chap. 5), and give rise to the **auditory-evoked startle reflex**.

7.3.2 The Superior Olivary Complex: Recreation of Auditory Space

The superior olivary complex is the first site for **binaural convergence**. In primates, the cochlear nuclei project to the superior olivary complex on both sides of the brain stem (Strominger 1973; Strominger et al. 1977). The **superior olivary complex** is located in the caudal pons, lateral to the medial lemniscus and dorsal to the spinothalamic tract. The complex contains the medial superior olivary nucleus, the lateral superior olivary nucleus and the nucleus of the trapezoid body. The latter nucleus is indistinct in apes and vestigial in humans (Moore 2000). The superior olivary complex is important for the **localization** of **sounds** (Moore and Linthicum 2004). A sound is localized by two means depending on its frequency: (1) low-frequency sounds activate the two ears at somewhat different times (interaural time differences); (2) high-frequency sounds activate the two ears with somewhat different intensities (interaural intensity differences). Neurons in the medial superior olivary nucleus are tuned to low-frequency stimuli and are sensitive to interaural time differences. The projection from the ventral cochlear nucleus is thought to contribute to this sensitivity. In contrast, neurons in the lateral superior olivary nucleus are tuned to high-frequency stimuli and are sensitive to interaural intensity differences. The lateral superior olivary nucleus receives a monosynaptic excitatory connection from the ipsilateral ventral cochlear nucleus and a disynaptic inhibitory connection from the contralateral ventral cochlear nucleus via the nucleus of the trapezoid body. Since the dorsal cochlear nucleus does not innervate the superior olivary complex, it is believed not to play a role in the localization of sounds.

Behavioural studies in cats have implicated the superior olivary complex in the **recreation** of **auditory space**. Cats with lesions above the level of the superior olivary complex, in the lateral lemniscus, the inferior colliculus, the MGB or the auditory cortex, are unable to locate a sound source in the spatial field contralateral to the lesion, whereas cats with lesions below the superior olivary complex have more diffuse deficits (Casseday and Neff 1975; Thompson and Masterton 1978; Jenkins and Masterton 1982). A comparable deficit has been observed in human subjects with extensive midline pontine lesions that eliminated crossed input to the superior olivary complex on both sides (Griffiths et al. 1997a; Furst et al. 2000; see ***Clinical case 7.2***). These animal and human studies suggest that the auditory spatial field is recreated in the brain stem by transformations occurring at the level of the superior olivary complex.

7.3.3 The Upper Brain Stem: Integration of Ascending Auditory Pathway

The **lateral lemniscus** is clearly visible in the rostral pons and the midbrain. Most of its fibres terminate in the inferior colliculus. Many of these fibres send a collateral branch to the nuclei of the lateral lemniscus, which innervate the inferior colliculus and also directly the MGB. In most mammalian

species, the lateral lemniscus contains sizable ventral, intermediate and dorsal lemniscal nuclei (Moore 1987). In humans, only the dorsal lemniscal nucleus is well developed (Geniec and Morest 1971; Moore 1987). It gives rise to Probst's commissure to the contralateral inferior colliculus.

The **inferior colliculus** is composed of three nuclei: central, external and pericentral. The **central nucleus** is the principal nucleus of the inferior colliculus and receives input from: (1) the direct pathway from the dorsal and ventral cochlear nuclei; (2) projections arising from the ipsilateral and contralateral superior olivary complex and (3) fibres from the dorsal nucleus of the lateral lemniscus. These projections all pass via the lateral lemniscus. The central nucleus is laminated (Geniec and Morest 1971) and processes the physical characteristics of sounds for auditory perception. In this nucleus, neurons in a single layer are maximally sensitive to similar tonal frequencies. The function of the other two nuclei of the inferior colliculus is not entirely clear. Lesion studies in cats suggest that the **external** and **pericentral nuclei** play a role in acousticomotor function such as the orientation of the head and body to auditory stimuli. The inferior colliculus projects to the MGB via the brachium of the inferior colliculus, which is macroscopically visible on the lateral surface of the midbrain. The inferior colliculi are interconnected via the commissure of the inferior colliculi.

7.3.4 Brain Stem Topography: Generation of Evoked Potentials

Waves I and II of the ABR are generated by the cochlear nerve. The subsequent waves III–VI are generated within the brain stem (see Fig. 7.5). Intrasurgical recordings made from the surface of the human brain stem and dipole studies suggest that wave III is generated by a volley of action potentials in axons emerging from the cochlear nuclei in the ventral acoustic stria (Stockard et al. 1978, 1986; Moller and Jannetta 1982; Scherg and von Cramon 1985). Waves IV and V are generated further rostrally in the brain stem: wave IV most likely at the level of the superior olivary complex contralateral to the stimulated ear, presumably by the bend in the axonal pathway occurring at that point, and wave V by synaptic activity in the inferior colliculus (Moller and Jannetta 1982; Moore et al. 1996).

Clinical Case 7.2 Impaired Sound Localization Following a Midline Pontine Lesion

In a 45-year-old female patient with an extensive **midline pontine lesion**, eliminating crossed input to the superior olivary complex on both sides, Griffiths et al. (1997a, b) observed that the patient had no difficulty in detecting frequency and amplitude modulation and no general deficit in detection of auditory temporal information, but she was *unable* to determine by sound alone the location and direction of motion of objects in the environment, such as ringing telephones and passing trains. Furst and co-workers analyzed sound localization in patients with multiple sclerosis and brain stem infarcts (Furst et al. 2000; 1995; Aharonson et al. 1998). Levine and Häusler (2001) reported another case (see **Case report**).

Case report: An 80-year-old male presented with sudden onset of vertigo and vomiting. On examination, he was found to have a left gaze palsy, dysphagia, dysarthria, and a right hemiplegia that included only the lower face. He had no auditory complaints, and his bedside hearing evaluation was unremarkable. MRI showed a left trapezoid body infarct, the location of which is indicated in Fig. 7.9a. A year later, he was evaluated with a battery of hearing tests. Despite an age-appropriate audiogram and normal BAERs, all fusion tests were abnormal for the three stimuli used (clicks, low-pass noise and high-pass noise) and for interaural time or level disparities (Fig. 7.9b). Just noticeable differences were highly abnormal, and regardless of the size or type of interaural disparity, the patient indicated that everything sounded as though it were coming from or near the centre of his head (Fig. 7.9c). Unlike normal subjects, nothing was heard coming from the far right or left.

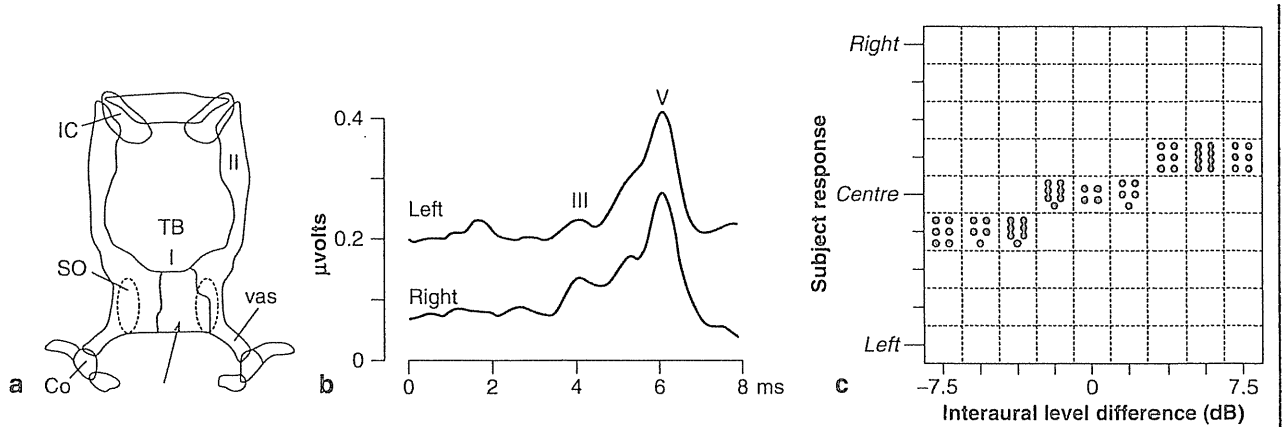

Fig. 7.9 Impaired sound localization in a patient with a lower pontine lesion (*arrow* in **a**) involving the trapezoid body; (**b**) brain stem auditory evoked responses; (**c**) sound lateralization (after Levine and Häusler 2001; see text for explanation). *Abbreviations*: *Co* cochlear nuclei; *IC* inferior colliculus; *II* lateral lemniscus; *TB* trapezoid body; *vas* ventral acoustic stria

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This case is based on a case report by Levine and Häusler (2001).

7.4 The Forebrain Auditory System

For decades, the dominant species for research on the auditory forebrain has been the cat, but the focus has now clearly shifted to non-human primates. Although the subcortical auditory systems of monkeys and cats are largely similar, there are important differences in cortical organization (Kaas and Hackett 2000).

7.4.1 The Auditory Thalamus

The **medial geniculate body (MGB)** or **nucleus** is clearly visible on the inferior surface of the inferior thalamus. The MGB contains several divisions, the principal auditory relay nucleus is the **ventral** or **principal medial geniculate nucleus** (Winer 1984). The ventral division of the MGB is laminated. It receives the major ascending auditory projection from the also laminated central nucleus of the inferior colliculus. For both nuclei, lamination is a structural correlate of precise tonotopic organization. In contrast, the dorsal and medial divisions of the MGB are not laminated and receive much less dense input from the inferior colliculus. The ventral medial geniculate nucleus projects via the auditory radiation to the tonotopically organized primary auditory cortex. The dorsal and medial subnuclei project to higher-order auditory cortical areas in the planum temporale, areas that do not have such a precise tonotopic organization as the primary auditory cortex.

7.4.2 The Acoustic Radiation

In 1882, Constantin von Monakow first described the origin of the acoustic radiation from the MGB in rabbit experiments. The classic studies in the human brain located the proximal part of the acoustic radiation just caudal to the thalamus, where it originates from the MGB, then passes through the sublenticular, posterior part of the internal capsule to curve around the inferior sulcus of the insula before reaching Heschl's gyrus

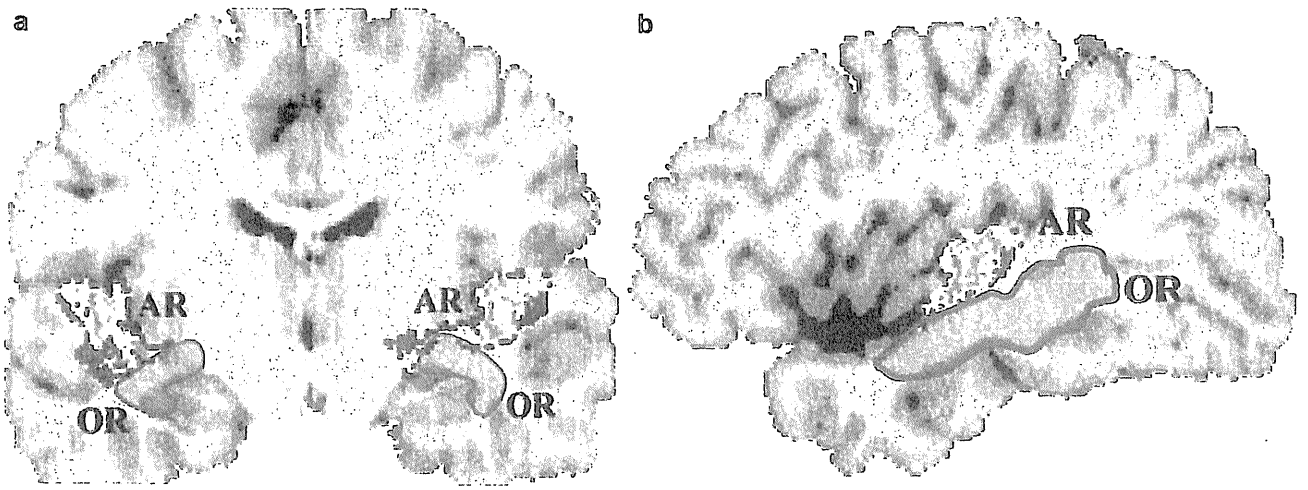

Fig. 7.10 The acoustic and optic radiations in coronal (**a**) and sagittal (**b**) probabilistic maps (after Rademacher et al. 2002). *Abbreviations*: *AR* acoustic radiation; *OR* optic radiation

(Dejerine 1895; Flechsig 1920; Pfeifer 1920). In a more recent study, Rademacher et al. (2002) showed the stereotaxic localization, intersubject variability and interhemispheric differences of the human acoustic radiation (Fig. 7.10). They showed that the location of the acoustic radiation varies considerably between individuals and hemispheres.

7.4.3 The Auditory Cortex: Sequential Levels of Auditory Processing

The **primary auditory cortex** (**A1**) is located on the transverse temporal or Heschl's gyrus in the temporal lobe of the cerebral cortex and corresponds to area 41. It is surrounded by secondary auditory areas (A2): caudally the caudomedial area, also known as the planum temporale, and rostrally, the rostral area. Geschwind and Levitsky (1968) demonstrated that the **planum temporale** is larger on the left side in the majority of the postmortem brains they examined. **Asymmetry** of the planum temporale may form the substrate for left hemispheric dominance for language-related auditory processes (Geschwind and Galaburda 1985; Dorsaint-Pierre et al. 2006) and is correlated with handedness (Steinmetz et al. 1989, 1991).

Heschl's gyrus is located largely within the lateral sulcus (von Economo and Horn 1930; Fig. 7.11). The transverse temporal gyrus is often partially duplicated into a double, or occasionally triple convexity (Pfeifer 1920; Steinmetz et al. 1989; Penhune et al. 1996; Leonard et al. 1998; Morosan et al. 2001). The cytoarchitecture of the human auditory cortex has been described by Brodmann (1908, 1909), von Economo and Koskinas (1925), Galaburda and Sanides (1980) and, more recently by Hackett et al. (2001) and Hackett

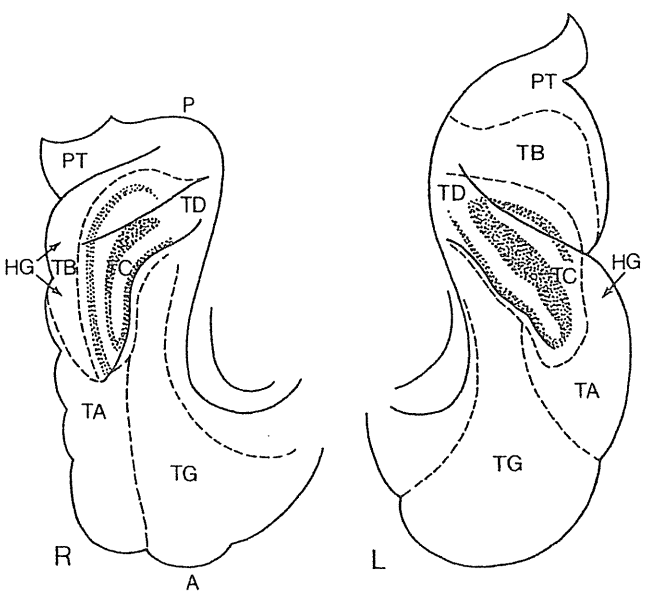

Fig. 7.11 The human auditory cortex. The primary auditory cortex is composed of two fields, TD and TC. On the right side (*R*), these occupy a double transverse temporal gyrus (Heschl's gyrus); on the left side (*L*), they correspond to a single Heschl's gyrus and a part of the more caudally situated planum temporale (*PT*). TD and TC are composed of markedly granular subareas (*dotted* in *red*) and less granular areas. Note the distinct right–left asymmetries with a larger planum temporale on the left side. *Abbreviations*: *A* anterior; *HG* Heschl's gyrus; *P* posterior; *TA* superior temporal area; *TB* magnocellular supratemporal area; *TC* transverse supratemporal area; *TD* intercalate supratemporal area; *TG* temporopolar area (after Brodal 1981)

and Kaas (2004) and Morosan et al. (2001) and Rademacher et al. (2001a, b). The primary auditory cortex was designated area 41 by Brodmann, TC by von Economo and Koskinas and

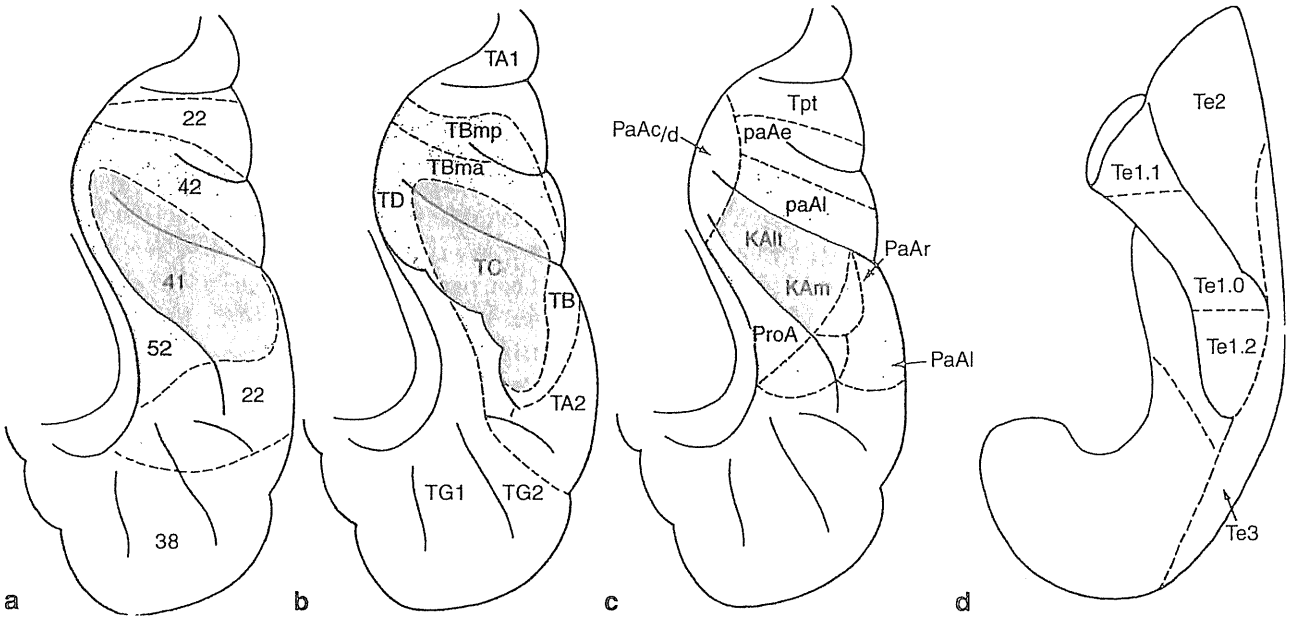

Fig. 7.12 Regional parcellation of the right human superior temporal cortex (rostral is below) according to (**a**) Brodmann, (**b**) von Economo and Koskinas, (**c**) Galaburda and Sanides and (**d**) Morosan and co-workers (after Hackett and Kaas 2004 and Morosan et al. 2001). In (**a–c**), core areas are shown in *red*, belt areas in *medium red* and parabelt areas in *light red*. *Abbreviations*: *Kalt*, *Kam* lateral and medial auditory koniocortex; *PaAc/d*, *paAe*, *PaAl/paAl*, *PaAr* caudal/dorsal, external, lateral and rostral auditory parakoniocortex; *ProA* proauditory cortex; *TA1*, *TA2*, *TB*, *TBma*, *TBmp*, *TC*, *TD* subdivisions by von Economo and Koskinas; *Te2*, *Te1.0*, *Te1.1*, *Te1.2*, *Te3* subdivisions by Morosan and co-workers; *TG1*, *TG2* temporopolar subdivisions of von Economo and Koskinas; *Tpt* temporoparietal area; *22–52* Brodmann areas

KAm and KAlt (medial and lateral auditory **koniocortex**) by Galaburda and Sanides (Fig. 7.12a–c). KAm is the most medial and the most granular area, whereas the more lateral KAlt is less granular. Morosan et al. (2001) suggested three areas with well-developed layers IV, Te1.1, Te1.0 and Te1.2, to represent the primary auditory cortex (Fig. 7.12d). There is considerable variability in size of the auditory koniocortex and its extent does not coincide with gyral or sulcal anatomy (Galaburda and Sanides 1980; Rademacher et al. 1993, 2001a, b; Hackett et al. 2001; Morosan et al. 2001). The human auditory koniocortex (area 41/TC/KA/Te) is homologous to the core area of the monkey auditory cortex. Based on parvalbumin staining, Wallace et al. (2002) suggested that Heschl's gyrus contains two core fields, partially surrounded by at least six belt fields that lie mostly on the superior temporal gyrus. In an fMRI study, Wessinger et al. (2001) showed that pure tones primarily activate the core and that more complex sounds activate belt areas.

The **primate auditory core area** is located in the centre of the superior temporal plane (Hackett et al. 2001; Fig. 7.13). In primates, a centrally located core region containing two or three subdivisions including the primary auditory area (A1), a surrounding belt of cortex with some seven divisions, and a lateral parabelt region comprised of at least two fields, have been described. In monkeys, the **core region** can be identified

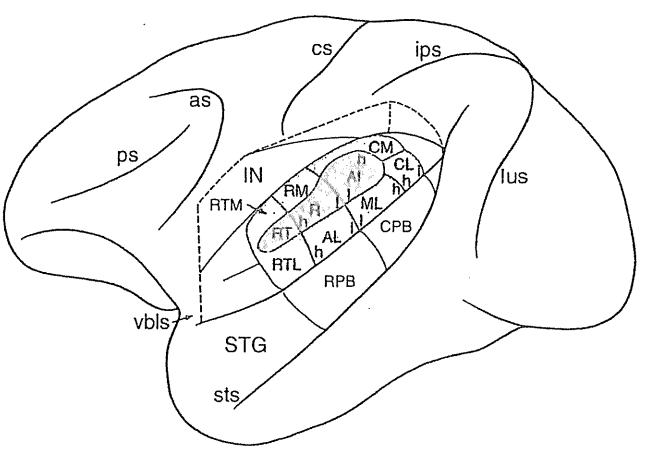

Fig. 7.13 Auditory and auditory-related cortices in macaque monkeys. Core areas (A1, R, RT) are shown in *red*, belt areas (CL, CM, AL, RM, RTL, RTM) in *medium red* and parabelt areas (CPB, RPB) in *light red*. Major sulci have been opened to show the extent of auditory-related cortex. *Abbreviations*: *A1* primary auditory area; *AL* anterolateral area; *as* arcuate sulcus; *CL*, *CM* caudolateral and caudomedial areas; *CPB* caudal parabelt area; *cs* central sulcus; *h*, *l* high and low frequencies; *IN* insula; *ips* intraparietal sulcus; *lus* lunate sulcus; *PL* posterolateral area; *ps* principal sulcus; *R* rostral area; *RM* rostromedial area; *RPB* rostral parabelt area; *RT* rostrotemporal primary auditory cortex; *RTL*, *RTM* lateral and medial rostrotemporal areas; *STG* superior temporal gyrus; *sts* superior temporal sulcus; *vbls* ventral bank of lateral sulcus (after Hackett et al. 2001)

on the basis of *specific* anatomical and physiological features. The region shows dense immunostaining for parvalbumin in layer IV, surrounded by a more lightly stained belt, which is flanked by a very sparsely stained parabelt (Jones et al. 1995; Kosaki et al. 1997). Parvalbumin staining also marks the human core auditory cortex in humans (Nakahara et al. 2000; Wallace et al. 2002; Chiry et al. 2003). In macaque, chimpanzee and human brains, Hackett et al. (2001) identified the auditory core from serial sets of adjacent sections processed for cytoarchitecture, myeloarchitecture, acetylcholinesterase and cytochrome oxidase. The position of the core region with respect to major sulci and gyri in the superior temporal region varied most in chimpanzee and human brains.

In monkeys, most neurons of the ventral division of the MGB project to the core cortex (Mesulam and Pandya 1973; Burton and Jones 1976; Luethke et al. 1989; Rauschecker et al. 1997). These **thalamocortical projections** terminate in layers IV and lower III in regular patches of higher density label, separated by areas of less dense labelling (Pandya and Rosene 1993; Hashikawa et al. 1995). In contrast, the medial and dorsal divisions of the MGB project to the core area diffusely. It seems likely that the human primary auditory cortex also receives dense thalamic input. This input explains the cochleotopic organization shown in this area by functional imaging, including magnetoencephalography (MEG) (Elberling et al. 1982; Hari et al. 1989; Pantev et al. 1995; Lutkenhoner and Steinstrater 1998), PET (Lauter et al. 1985; Ottaviani et al. 1997; Lockwood et al. 1999), fMRI (Wessinger et al. 1997; Scheich et al. 1998; Di Salle et al. 2001) and microelectrode mapping studies in epilepsy patients (Howard et al. 1996).

The human auditory koniocortex is surrounded rostrally, laterally and caudally by an area of **parakoniocortex** (Fig. 7.12). This region covers the lateral part of the transverse temporal gyrus, and extends rostrally and caudally over the superior temporal plane. The auditory parakoniocortex has been called area 42 by Brodmann and TB by von Economo and Koskinas. Galaburda and Sanides (1980) distinguished three regions: (1) a rostral auditory parakoniocortex (PaAr) on the rostral aspect of the superior temporal plane; (2) a lateral, internal auditory parakoniocortex (PaAl), lateral to A1; and (3) a caudal auditory parakoniocortex (PaAc), covering the caudal portion of the superior temporal plane and extending around the insula to the parietal operculum. In its turn, the parakoniocortex is surrounded by an extensive area of auditory cortex that covers the remaining of the superior temporal plane and the lateral surface of the superior temporal gyrus, except for its rostral pole. This region was described as area 22 by Brodmann (1909), as TA by von Economo and Koskinas (1925) and as external auditory parakoniocortex (PaAe) by Galaburda and Sanides (1980).

In primates (Fig. 7.13), anatomical and physiological studies defined a **belt area** surrounding the core rostrally, laterally and caudally (Pandya and Sanides 1973; Galaburda and Pandya 1983; Morel and Kaas 1992; Morel et al. 1993; Hackett et al. 1998a). The area rostral and lateral to the belt is nowadays known as the **parabelt** (Morel et al. 1993; Hackett et al. 1998a). Both belt and parabelt areas differ from the core area in their pattern of thalamic input. The macaque belt area receives projections from only the medial and dorsal divisions of the MGB (Rauschecker et al. 1997), whereas the parabelt area is also innervated by these two divisions of the MGB but, moreover, by the medial division of the pulvinar (Trojanowski and Jacobson 1975; Burton and Jones 1976; Hackett et al. 1998b).

Ablation of the core of macaque auditory cortex eliminates responses to auditory stimuli in the adjacent belt region (Rauschecker et al. 1997), suggesting that input from the medial and dorsal geniculate nuclei is not sufficient to support auditory processing in the absence of direct projections from the ventral geniculate nucleus. Instead, information processing to the secondary auditory cortical areas appears to depend on transcortical projections that pass successively from core to belt to parabelt cortex (Jones and Powell 1970; Seltzer and Pandya 1978; FitzPatrick and Imig 1980; Luethke et al. 1989; Morel and Kaas 1992; Morel et al. 1993; Hackett et al. 1998a). Tardif and Clarke (2001) studied the intrinsic connectivity of human auditory areas with anterograde and retrograde labelling of the carbocyanine dye DiI. With DTI, the tracts connecting the Heschl's gyri via the corpus callosum have been studied (Hofer and Frahm 2006; Westerhausen et al. 2009). These interhemispheric connections are located more rostrally within the posterior callosal third than those connecting the posterior parts of both superior temporal gyri.

The idea of a two-stream, **what/where** organization of sensory cortex originated in the visual system (see Chap. 8). In rhesus monkeys, such a dichotomy has also been demonstrated for the cortical auditory projections (Rauschecker and Tian 2000). The **'where' (dorsal) pathway** is thought to link A1 via the caudomedial belt with the frontal eye field and parietal targets (Romanski et al. 1999; Fig. 7.14) that are implicated in *spatial processing*. The **'what' (ventral) pathway** is thought to represent a *pattern information* stream that originates in the anterior core and belt areas and influences targets within the temporal lobe. A similar **two-stream organization** may exist in the human auditory cortex (Griffiths et al. 2000; Alain et al. 2001; Maeder et al. 2001; Wessinger et al. 2001; Clarke et al. 2002). The right insula is activated by a moving sound image (Griffiths et al. 1994) and, conversely, a patient with a right hemispheric stroke causing atrophy of the right insula was unable to detect sound source movement by either phase or loudness cues (Griffiths et al. 1996). Subjects listening to stimulus movement stimulated by changes in binaural timing show maximal activity in the inferior parietal area, particularly on the right side (Griffiths et al. 1998; Weeks et al. 1999). These findings suggest: (1) that there is a transcortical passage of information from

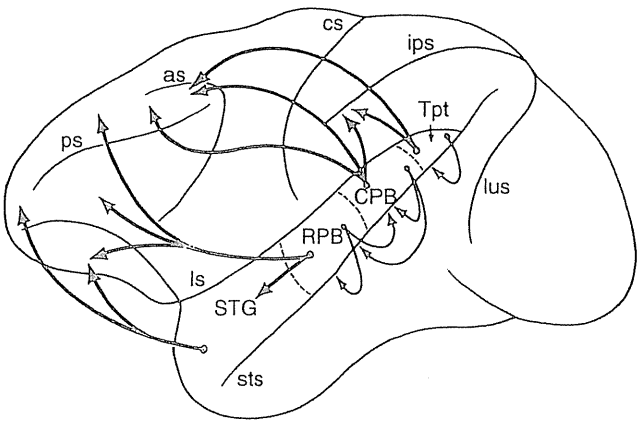

Fig. 7.14 Topography of auditory-related projections. Caudal (*CPB*) and rostral (*RPB*) subdivisions of the parabelt and the superior temporal gyrus (*STG*) project topographically to segregated regions of superior temporal, posterior parietal and prefrontal cortices. *Abbreviations*: *as* arcuate sulcus; *cs* central sulcus; *ips* intraparietal sulcus; *ls* lateral sulcus; *lus* lunate sulcus; *ps* principal sulcus; *sts* superior temporal sulcus; *Tpt* temporoparietal area (after. Hackett and Kaas 2004)

auditory koniocortex mediocaudalwards across the insula into the parietal lobe, during processing of information on sound source position and motion (see Hackett and Kaas 2004); and (2) a dominant functional role of the right hemisphere in sound localization.

In **functional imaging studies**, simple auditory tasks such as passive listening to white noise bursts, tones or consonant-vowel speech syllables, activate restricted areas within the lateral fissure on the superior temporal plane (Zatorre et al. 1992, 1994; Binder et al. 1994, 1997, 2000; Zatorre and Binder 2000). The extent of the activation varies from subject to subject and may spread rostralwards and caudalwards on the superior temporal plane. The area of activation is generally within and around the transverse temporal gyrus. With exposure of subjects to more complex stimuli such as passive listening to tone patterns, single words, pseudowords or narrative text, activity is not only present in the cortex of the superior temporal gyrus, but now foci of activation appear on the lateral aspect of the superior temporal gyrus in area 22/TA/PaAc (Binder et al. 1994). The human primary auditory cortex is functionally organized in a **tonotopic manner**. In a combined fMRI and DTI study, Upadhyay et al. (2007) showed that the connectivity pattern in the human primary auditory cortex is similar to that described in tonotopic mapping studies on macaque monkeys (Morel et al. 1993) and cats (Lee et al. 2004; Lee and Winer 2005).

In general, activity is **bilaterally equal**. With complex stimuli, language in particular, the question arises whether there is a right–left asymmetry in the response. Since handedness influences hemipheric lateralization, imaging studies of speech processing are normally restricted to neurologically normal right-handers. In them, there is a tendency for greater activation of the left hemisphere during tasks that depend on word meaning. Left lateralization of speech characterizes both males and females (Frost et al. 1999). The functional significance of greater left hemispheric activity is implied by imaging studies of stroke patients after infarctions of the left perisylvian area (Weiller et al. 1995; Heiss et al. 1997; Mummery et al. 1999). Subjects who showed good recovery of speech perception had increasing activation of the left temporal cortex surrounding the infarct. Some indications for an **opposite asymmetry** in processing **musical stimuli** come from cases of pathology:

1. A patient with a **right** thalamic tumour experienced ***distorted perception*** of ***music*** but not of voices (Roeser and Daly 1974).
2. Cortical activity has been demonstrated in the right superior temporal lobe during ***musical hallucinations*** (Kasai et al. 1999).
3. A case of ***amusia***, a form of auditory agnosia, was seen after an infarct involving the right insula (Griffiths et al. 1997b).

7.4.4 Auditory Disorders Related to Stroke

Disorders of auditory perception may follow strokes in the territory of the internal carotid arteries or of the vertebrobasilar system (Levine and Häusler 2001; Lechevalier et al. 2007; Kaga 2009), and appear as:

- ***Auditory agnosia***, the impossibility of recognizing environmental sounds, words and music, which the patient, however, is said to hear
- ***Pure word deafness***, the impossibility to understand spoken language to repeat or to write under dictation in the absence of other signs of aphasia
- ***Cortical deafness***, the feeling of being deaf contrasting with the integrity of the tonal audiogram
- ***Amusia***, auditory agnosia specific for music

The central disorders of auditory perception may result from lesions of either the right, the left or both cerebral hemispheres, usually involving parietotemporal cortical areas. ***Cortical deafness*** is characterized by bilateral abolition of the middle and late latencies of auditory potentials, caused by bilateral lesions of the primary auditory cortices. Such patients have the feeling of being deaf to all types of auditory stimuli, but often say they are *not* deaf, rather that they do not understand what is said to them. The term ***subcortical deafness*** is used to indicate an auditory disorder clinically identical to cortical deafness, but due to lesions in subcortical areas of the brain. It was first described by Le Gros Clark and Russell (1938). The ischaemic lesions involved the two external capsules and extended sufficiently downwards to interrupt the acoustic radiations, while sparing the auditory cortices. Recent cases were reported by Woods (1996), Levine and Häusler (2001) and Kaga et al. (2005; see ***Clinical case 7.3***).