FUNCTIONAL ANATOMY OF THE HUMAN COCHLEAR NERVE AND ITS ROLE IN MICROVASCULAR DECOMPRESSIONS FOR TINNITUS

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OBJECTIVE: The functional anatomy (i.e., tonotopy) of the human cochlear nerve is unknown. A better understanding of the tonotopy of the central nervous system segment of the cochlear nerve and of the pathophysiology of tinnitus might help to ameliorate the disappointing results obtained with microvascular decompressions in patients with tinnitus.

METHODS: We assume that vascular compression of the cochlear nerve can induce a frequency-specific form of hearing loss and that when the nerve is successfully decompressed, this hearing loss can recuperate. Thirty-one patients underwent a microvascular decompression of the vestibulocochlear nerve for vertigo or tinnitus. Preoperative audiograms were subtracted from postoperative audiograms, regardless of the surgical result with regard to the tinnitus and vertigo, because the hearing improvement could be the only sign of the vascular compression. The frequency of maximal improvement was then correlated to the site of vascular compression. A tonotopy of the cochlear nerve was thus obtained.

RESULTS: A total of 18 correlations can be made between the site of compression and postoperative maximal hearing improvement frequency when 5-dB hearing improvement is used as threshold, 13 when 10-dB improvement is used as threshold. A clear distribution can be seen, with clustering of low frequencies at the posterior and inferior side of the cochlear nerve, close to the brainstem, and close to the root exit zone of the facial nerve. High frequencies are distributed closer to the internal acoustic meatus and more superiorly along the posterior aspect of the cochlear nerve.

CONCLUSION: The tonotopic organization of the cisternal segment of the cochlear nerve has an oblique rotatory structure as a result of the rotatory course of the cochlear nerve in the posterior fossa. Knowledge of this tonotopic organization of the auditory nerve in its cisternal course might benefit surgeons who perform microvascular decompression operations for the vestibulocochlear compression syndrome, especially in the treatment of unilateral severe tinnitus.

KEY WORDS: Cochleovestibular compression syndrome, Disabling positional vertigo, Microvascular compression, Microvascular decompression, Tinnitus, Tonotopy

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The vestibulocochlear nerve is composed of three parts: the cochlear nerve and the inferior and superior vestibular nerves. The two vestibular nerves join to become one nerve before their exit from the internal acoustic meatus. The vestibular nerve and cochlear nerve fuse to form the eight cranial nerves closer to the brainstem (55). The vestibular and cochlear components can be distinguished in a surgical setting by a fine blood vessel running along the eighth nerve (54). The cochlear component appears whiter than the vestibular component because it contains more nerve fibers (30,000 versus 18,000) and thus more myelin (54, 55). Like other cranial nerves, the vestibulocochlear nerve is twisted. Close to the brainstem, the auditory portion is located caudally with respect to the vestibular portion, and it is located anteriorly to the inferior vestibular nerve in its most peripheral portion in the internal acoustic canal. This results in a 90-degree rotation (54). This anatomic knowledge is important because it affects the tonotopic structure of the cochlear nerve.

The auditory system in mammal species, including cat, rat, gerbil, chinchilla, mouse, and hamster, is tonotopically organized at the level of the cochlea (18, 32), brainstem, and auditory cortex (4, 18, 32). Only in the cat has this tonotopy been analyzed in the cochlear nerve as well (1, 51). In humans, the tonotopic structure of the cochlea and cortex has been demonstrated functionally by magnetoencephalography (41) and functional magnetic resonance imaging (MRI) (61). Similarly, a tonotopic structure has been suggested in the peripheral segment of the cochlear nerve (9, 55) on the basis of histological studies. The tonotopy of the neurosurgically more accessible cisternal or central nervous system (CNS) segment, however, is unknown as a result of the diffuse anatomic structure of the CNS segment of the vestibulocochlear nerve (5, 57).

Knowledge of the tonotopy of the CNS segment might help in defining diagnostic and prognostic criteria for microvascular decompressions (MVDs) in patients with tinnitus because there is a correlation between the frequency of hearing loss and tinnitus frequency in microvascular compressions associated with tinnitus (V Nowé, D De Ridder, PH Van de Heyning, XL Wang, J Gielen, J Van Goethem, Ö Özsarlak, AM De Schepper, PM Parizel, submitted for publication). Microvascular contacts with cranial nerves are associated with a variety of symptoms, such as trigeminal neuralgia, hemifacial spasm, glossopharyngeal neuralgia, and disabling positional vertigo (14). These disorders can be treated successfully by MVD operations, which have outcomes ranging from 85 to 75%, respectively, at 1 and 10 years after decompression for most microvascular compression syndromes (2, 3, 13). Surgical results of MVDs performed in the treatment of isolated tinnitus have a worse prognosis, with a success rate of approximately 40 to 65.5% (37, 50). Once hearing is severely impaired, high-pitch nonpulsatile tinnitus may not be cured by MVD (49). In a similar trend, there is a clear correlation between the preoperative duration of the tinnitus and the results of MVD, where 3 years seems to be a cutoff point for surgical success (37, 49). Complicating matters further is the fact that the vestibulocochlear nerve is frequently in contact with blood vessels in the cerebellopontine angle; the frequency of such vascular contact in asymptomatic individuals has been reported to be as high as nearly 60% (42). Comparison between such vascular contact between the eighth cranial nerve and a loop of the anteroinferior cerebellar artery by MRI scans showed such contact in 25% of patients with symptoms from the eighth cranial nerve and in 21.4% of asymptomatic individuals (24). The success of the MVD operation for specific vestibular and auditory symptoms has provided overwhelming evidence that such vascular contact is involved in producing symptoms and signs (21, 26, 29, 50, 59). There is also overwhelming anatomic evidence from both postmortem studies (19, 25, 40, 56) and imaging studies (24, 42) that vascular contact from the vestibulocochlear nerve can exist without producing symptoms and signs. Whether this is the result of morphological factors essential for producing symptoms that have escaped detection or whether the same vascular contact can exist in individuals with or without symptoms is unknown. If the latter is the case, then there must be yet-undiscovered factors that are necessary for producing symptoms but that, alone, do not produce noticeable symptoms, as has been suggested in connection with other cranial nerve disorders that can be treated successfully by MVD operations (29, 31).

It has been recently argued that for vascular compression to become symptomatic, the compression has to occur at the CNS segment of the cranial nerve (5). The length of this CNS segment differs for all cranial nerves; for the cochlear nerve, the CNS segment equals the whole cisternal segment because the root entry zone is usually located at the internal acoustic meatus (20). Because there is a clear correlation between the length of this CNS segment and the incidence of the associated microvascular compression syndrome (5), we would expect the cochleovestibular compression syndrome to be the microvascular compression syndrome with the greatest prevalence. Knowing the functional anatomy (i.e., tonotopy) of the cisternal segment could benefit the diagnosis, treatment, and prognosis of the vestibulocochlear nerve compression syndrome.

PATIENTS AND METHODS

To test this tonotopic organization, we assume that a vascular compression of the (vestibulo)cochlear nerve can induce frequency-specific forms of hearing loss, and that when the nerve is successfully decompressed, this hearing loss can recuperate, similar to the improvement seen in MVDs performed for sudden deafness (46). A total of 31 patients were decompressed by one of the authors (HR) for a microvascular compression syndrome of Cranial Nerve VIII (48, 49). Pre- and postoperative audiograms were digitalized, subtracted from each other, and normalized to contralateral to evaluate what specific frequencies improved after an MVD of the vestibulocochlear nerve. Postoperative audiograms were taken 2 years after surgery and were almost identical to the 1-year postoperative audiograms. The results were analyzed regardless of the surgical result with regard to tinnitus and vertigo because the hearing improvement could be the only sign of vascular compression. The frequency of maximal improvement was then correlated to the site of vascular compression. A tonotopy of the cochlear nerve was thus obtained.

Because in a clinical setting patients can only distinguish between high-pitch and low-pitch nonpulsatile tinnitus, we divided the patient population into two groups on the basis of the frequency of maximal improvement postoperatively: a low-frequency group with maximal improvement frequencies of 250 to 500 Hz, and a high-frequency group with maximal improvement of 1000 to 8000 Hz. Further refinements could be made, including the creation of a midfrequency group (1000–2000 Hz), but this is not clinically relevant, and our data are insufficient for that purpose.

RESULTS

A total of 31 patients were reviewed, all with pre- and postoperative ipsilateral and contralateral audiograms. Of these, 20 patients had improvement of 5 dB or more postoperatively, and 15 patients had improvement of 10 dB or more (*Table 1*). In 29 of 31 patients, the site of vascular compression is known, resulting in 18 correlations between the site of compression and postoperative maximal hearing improvement frequency when 5 dB is used as threshold, 13 when 10-dB improvement is used as threshold (*Table 1*; *Fig. 1, A* and *B*).

A clear distribution can be observed clustering low frequencies at the posterior and inferior side of the cochlear nerve, close to the brainstem, and close to the root exit zone of the facial nerve. High frequencies are distributed closer to the internal acoustic meatus and superior along the posterior aspect of the cochlear nerve. Decompression at the posterior and inferior side of the cochlear nerve leads to a marked improvement of the low frequencies (mean, 10-dB improvement [standard deviation [SD], 4 dB] for 250 Hz; mean, 6.25-dB improvement [SD, 2.5 dB] for 500 Hz) in comparison to the high frequencies where, on average, a hearing loss is noted (mean, 6.25-dB hearing loss [SD, 11 dB] for 4000 Hz; mean, 2.5-dB hearing loss [SD, 5 dB] for 8000 Hz). Decompression at the posterior and superior aspect of the cochlear nerve provides less pronounced differences, resulting in a mean hearing improvement of 3.75 dB for both 4000 and 8000 Hz (SD, 5 and 8 dB, respectively) and a mean improvement of 2 dB (SD, 6 dB) for 250 Hz and 1.25 dB for 500 Hz (SD, 7.5 dB). No major differences are seen when 5-dB improvement or 10-dB improvement is used as a threshold in relation to the site of compressions (*Table 1*; *Fig. 1*).

We do not expect the tonotopy to be perfectly identical in every individual, similar to the variation in the somatotopic distribution of the dermatomes. One possible explanation for this could be that the 90-degree rotation in the cisternal part of its trajectory might differ slightly among individuals. For example, if the rotation in *Figure 1C* is somewhat less accentuated, the lower frequencies will lie more dorsally, closer to the internal acoustic meatus, possibly explaining why in Patient 3 the lower frequencies (500 Hz) also improved postoperatively, although in a less pronounced way. The idea here is that vascular compression results in a conduction block or demyelination with conduction dysfunction of the compressed fibers (8, 28, 52). We thus assume that only the site of sufficient compression will generate a functional (i.e., tonotopically specific) hearing impairment. This explains why even in broad-based compressions, relatively narrow hearing deficits can occur. To minimize the interindividual functional anatomic differences, only the frequency of maximal postoperative improvement is considered in the analysis.

To minimize measuring errors between pre- and postoperative audiometry, the subtracted audiograms (preoperative minus postoperative) are normalized to contralateral (*Figs.* 2 and 3, *A* and *B*). This is done by subtracting contralateral preoperative minus postoperative audiograms from the ipsilateral preoperative minus postoperative audiograms. No major differences are noted when normalization is performed compared with nonnormalized audiogram subtractions (*Table 1*).

Three interesting patients (Patients 8, 12, and 31) reveal a double peak of improvement of the hearing threshold, one at low frequencies and one at high frequencies (*Fig. 3D*). All three had double vascular compression (*Fig. 1, A* and *B*). We opted to accept each compression to generate one form of hearing loss, and we considered the low-frequency improvement to be attributable to the posterolateral decompression closest to the brainstem and the high-frequency hearing improvement to be caused by the release of a more medial and distal compression. This strengthens our idea of how the tonotopy is distributed in the cochlear nerve, but we agree that it could be considered the opposite as well. Only frequency-specific brainstem auditory evoked potentials could prove or disprove this suggestion, the idea being that it could in theory be abnormal for only the compressed nerve fibers and not the uncompressed nerve fibers.

Twenty-nine of 31 patients presented with tinnitus. In 15 patients (52%), the tinnitus resolved postoperatively, and in 4 (14%), it markedly improved, with a total of 19 (66%) of 29 patients experiencing a good outcome. Ten patients did not benefit from the decompression (*Table 1*).

DISCUSSION

Tonotopy

The auditory nervous system as a whole is organized anatomically according to the frequency neurons respond best to. This tonotopic organization has been described in many studies in animals (4, 18, 32) and is a result of the separation of sounds according to their frequency, or spectrum, which occurs in the cochlea. The tonotopic organization of the cat's cochlear nerve has been described in detail (1, 51), and it has been suggested to be present in the peripheral nervous system segment as well (i.e., the intrameatal segment of the human cochlear nerve based on histological sections). Therefore, we expect the CNS segment of the cochlear nerve to be organized in a tonotopic way, too.

Histological analysis is not a confirmation of this functional distribution in the CNS segment of the cochlear nerve. The tonotopy can be followed in the peripheral part of the cochlear nerve by superposition of the windings of the cochlea on the funiculi of the cochlear nerve (55). The funicular structure disappears after entry into the CNS segment of the cochlear nerve (i.e., the cisternal part). Furthermore, in the human, there seem to be no caliber differences between the apical and basal fibers (9, 55), contrary to the reported differences in guinea pig and mouse (55), thus not permitting the tracing of the different fibers in the CNS segment or cisternal segment of the cochlear nerve. Therefore, histological studies are of no help in clarifying the tonotopy of this part of the vestibulocochlear nerve.

Electrophysiological studies performed intraoperatively (35, 36) demonstrated the difficulties of mapping the cochlear nerve. One problem is associated with the spread of activity in

TABLE 1. Patient characteristics[a]

Case no.	Patient no.	Age (yr)/sex	Side	Tinnitus	Tinnitus resolved	Hearing improvement	≥5 dB	≥10 dB	Preoperative-postoperative (maximum dB improvement)	Preoperative-postoperative normalized	Compression site known
1	1	61/F	R	+	–	–					Yes
2	3	47/M	L	+	+	+		+	1000	1000	Yes
3	4	24/M	R	+	+	–					Yes
4	5	53/M	L	+	–	+	+		8000	4000–8000	Yes
5	7	53/M	L	+	+	–					Yes
6	8	53/M	R	+	–	+		+	500 + 2000	500 + 2000	Yes
7	9	31/F	L	+	i	+	+		250–500	500	Yes
8	10	52/F	L	+	–	–					Yes
9	12	47/F	R	+	+	+		+	250–500 + 4000–8000	250–500 + 4000–8000	Yes
10	13	54/M	R	+	–	+		+	2000–4000	2000–4000	No
11	14	68/F	R	+	+	+	+	8000	4000–8000	Yes	
12	15	42/F	R	+	–	+		+	4000	2000	Yes
13	16	46/M	L	+	+	–					Yes
14	17	46/F	R	+	–	+		+	1000	1000	No
15	18	38/F	R	–		–					Yes
16	21	53/F	L	+	+	–					Yes
17	23	43/M	L	+	+	+		+	2000–8000	4000–8000	Yes
18	25	64/M	L	+	–	–					Yes
19	29	49/M	L	+	i	+		+	2000–8000	2000–8000	Yes
20	30	50/F	R	+	+	+		+	8000	8000	Yes
21	31	67/F	R	+	+	+		+	250–500 + 4000–8000	250–500 + 4000–8000	Yes
22	33	73/F	L	+	+	+	+		250–1000	250–500	Yes
23	34	44/M	R	+	+	+		+	2000	2000–4000	Yes
24	35	52/M	L	+	+	+	+		4000	4000–8000	Yes
25	36	48/M	L	+	i	+		+	250–2000	250–1000	Yes
26	38	42/M	R	+	+	+		+	8000	8000	Yes
27	39	58/M	L	+		+	+		4000	2000–4000	Yes
28	40	61/M	L	+	–	–					Yes
29	41	42/F	R	–		–					Yes
30	42	45/M	L	+	+	+		+	500	500	Yes
31	43	44/F	L	+	i	–					Yes

[a] R, right; L, left; +, present; –, absent; i, improved.

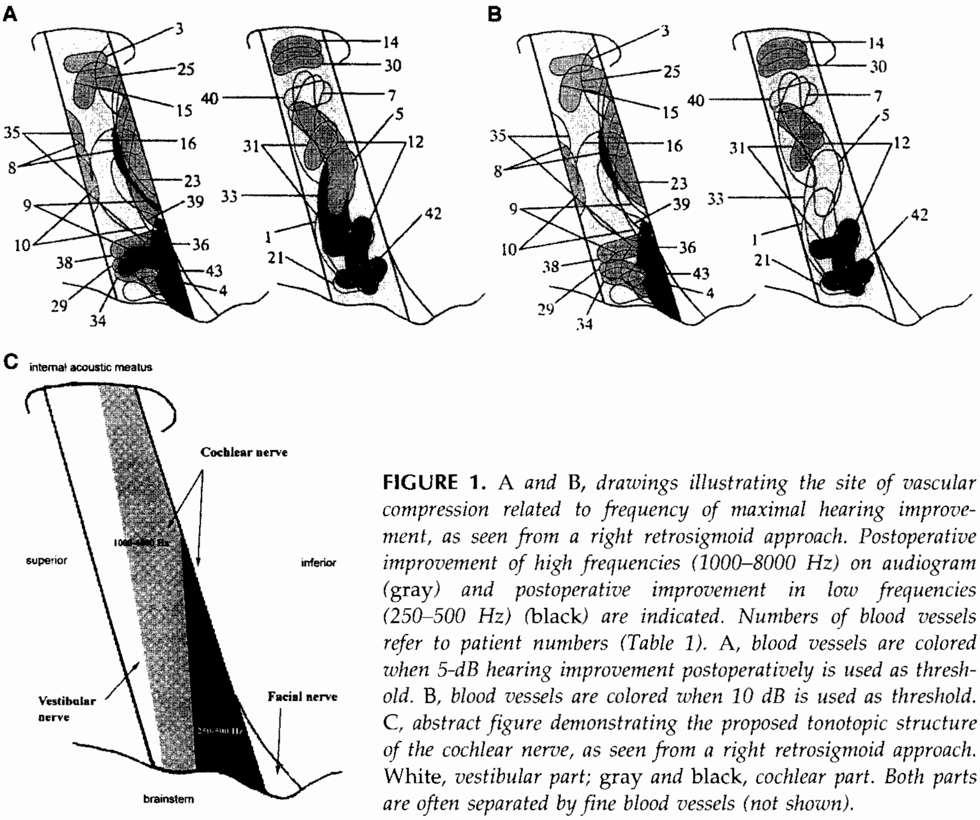

FIGURE 1. A *and* B, *drawings illustrating the site of vascular compression related to frequency of maximal hearing improvement, as seen from a right retrosigmoid approach. Postoperative improvement of high frequencies (1000–8000 Hz) on audiogram (*gray*) and postoperative improvement in low frequencies (250–500 Hz) (*black*) are indicated. Numbers of blood vessels refer to patient numbers (Table 1).* A, *blood vessels are colored when 5-dB hearing improvement postoperatively is used as threshold.* B, *blood vessels are colored when 10 dB is used as threshold.* C, *abstract figure demonstrating the proposed tonotopic structure of the cochlear nerve, as seen from a right retrosigmoid approach.* White, *vestibular part;* gray *and* black, *cochlear part. Both parts are often separated by fine blood vessels (not shown).*

the auditory nerve when high sound intensities are used. The use of lower sound intensities requires a longer time for averaging the evoked potentials, making it impractical to do such recordings in the operating room (35, 36). A theoretically better method for verification of the tonotopy of the auditory nerve would be to obtain a pure tone audiogram in the awake patient intraoperatively in response to electrical stimulation of the cochlear nerve at different sites of the cisternal segment.

Clinical arguments relating to the tonotopy of the cochlear nerve come from the work of Møller and Møller (34) on hemifacial spasm, in which they noted that if the neurovascular conflict results in hemifacial spasm with associated hearing loss, the hearing loss is of the low-frequency type. In the series of Ryu et al. (50), 6 of 10 patients with hemifacial spasm associated with tinnitus presented with a low-pitch tinnitus. Those with high-pitch tinnitus either had two different blood vessels compressing the cochlear and facial nerve or a compression that extended to the high-frequency area of the cochlear nerve.

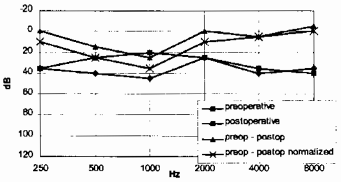

FIGURE 2. *Audiograms for Patient 3. A 25-dB hearing improvement is noted at 1000 Hz.*

Tinnitus

Recently, some forms of tinnitus have been considered to be auditory phantom phenomena (15, 30, 60), similar to central neuropathic pain (30) or other forms of pain (60). These phantom phenomena are thought to be the result of cortical reorganization, thus altering the normal tonotopic map (10, 39). The tonotopic map can become reorganized in reaction to any abnormal pattern of neural activity from the periphery (12). Therefore, the reorganization probably starts peripherally and ends cortically (11, 12, 62), in the same way the development of tonotopic organization occurs: namely, first in the brainstem auditory nuclei, later in the midbrain, and finally in the forebrain, as demonstrated by positron emission tomographic studies in the gerbil (47).

Tinnitus is accompanied by a change of the tonotopic map in the auditory cortex (39, 44). Furthermore, there is a high positive association between subjective tinnitus strength and the amount of shift of the tinnitus frequency in the auditory cortex (39), in the same way that there is a very strong correlation between the amount of reorganization of the somatosensory cortex and the amount of phantom limb pain (10).

In humans with tinnitus, the inferior colliculus (27) is involved, as well as the auditory cortex (27, 39, 44), which has several tonotopically organized areas (58). The reorganization may also

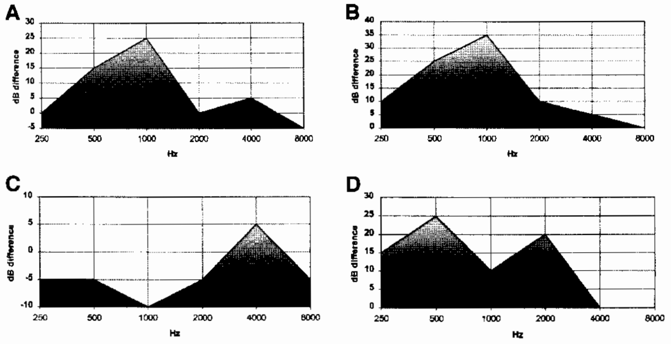

FIGURE 3. *Graphs illustrating hearing improvement.* A *and* B, *hearing improvement plotted for Patient 3 with 25-dB hearing improvement postoperatively at 1000 Hz. Pre- and postoperative audiograms are subtracted* (A) *and normalized to contralateral* (B), *showing similar frequencies of maximal improvement.* C, *Patient 35, 5-Hz hearing improvement isolated at 4000 Hz.* D, *biphasic hearing improvement, 25 dB at 500 Hz and 20 dB at 2000 Hz. Note that Patient 35 has two vascular compressions in Figure 1, A and B, and we assume one compression is responsible for the high-frequency hearing impairment preoperatively and one for the low-frequency hearing impairment. The same is true for Patients 8 and 12.*

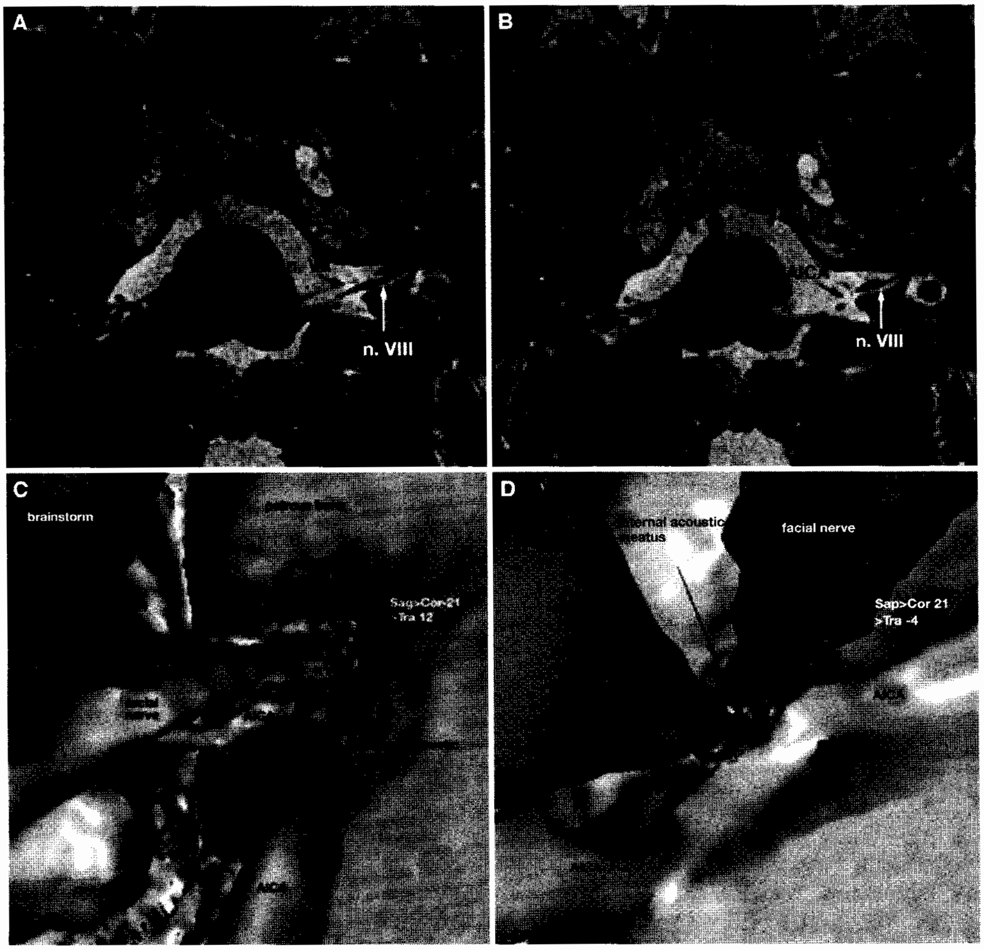

FIGURE 4. A *and* B, *0.6-mm CISS-weighted images. A close vascular-nervous relationship can be seen. Resolution is insufficient to ascertain whether a real vascular compression is present.* C *and* D, *high-resolution (0.6 mm) CISS-weighted images with three-dimensional reconstruction. No vascular compression is present anywhere on the auditory nerve.* AICA, *anteroinferior cerebellar artery;* Sag, *sagittal;* Cor, *coronal;* Tra, *transverse;* n., *cranial nerve.*

involve activation of other parts of the CNS. Evidence has been presented that the nonclassical auditory pathways may be involved in some forms of tinnitus (38) and thereby may provide a direct subcortical route to the amygdala (22, 33). The hypothesis that limbic structures are abnormally involved in some forms of tinnitus has been supported by functional MRI studies (23).

Tinnitus and Tonotopy in Microvascular Compressions

To explain tinnitus in view of these recent findings, we hypothesize the following pathophysiological mechanism: microvascular compressions cause a dysmyelination and demyelination of the underlying zone of the cochlear nerve (8, 28, 52), resulting in an abnormal signal transmission to the auditory cortex (11, 12, 47, 62) for these specific tones. The resulting auditory tract and cortical reorganization (16–18, 43, 45) leads to a tinnitus that matches the frequency of the compressed cochlear nerve fibers.

This hypothesis is supported by findings in other cranial nerves; it has been shown that abnormal activation (electrical stimulation) of the facial nerve can cause signs that are similar to those of hemifacial spasm (53), resulting in hyperactivity and reorganization of the facial motonucleus (29). There are also similarities between some forms of tinnitus and pain disorders (30), such as trigeminal neuralgia and some forms of central neuropathic pain caused by slight injury or abnormal stimulation of cranial nerves and peripheral nerves (6–8). These disorders (spasm and neuropathic pain) all are associated with reorganization of the specific structures in the CNS and thus are similar to what has been observed in patients with tinnitus.

Correlating the maximal improvement from the hearing deficit to the site of compression results in a tonotopic organization of the cochlear nerve. Our results demonstrate an oblique rotatory organization of the Cranial Nerve VIII as it approaches the brainstem. This is in agreement with the known anatomy of Cranial Nerve VIII (54). The cochlear nerve lies anteriorly (anterior of the inferior vestibular nerve) at the level of the labyrinth and rotates to come and lie laterally (of the vestibular nerve) and posteriorly at the level of the brainstem (54) (*Fig. 1C*).

Knowledge of tonotopy might help define which patients could benefit from MVDs for unilateral tinnitus. It is well known that vascular compressions of cranial nerves occur frequently without symptoms or signs. Asymptomatic compression of the vestibulocochlear nerve has been reported in many postmortem studies (19, 25, 40, 56) and imaging studies (24, 42). Although severe tinnitus is rare, vascular contact is common (as much as 50–70%) and is likely to occur together with vascular compression. This means that vascular contact is most likely a necessary (but not sufficient) condition for severe tinnitus. It is therefore important to know whether a patient with severe tinnitus has a vascular conflict with the auditory nerve, and it is important to correlate the perceived frequency of the tinnitus with the location of the vascular contact on the auditory nerve.

Knowledge regarding the exact location of a vessel on the auditory nerve can be obtained by high-resolution MRI, but such knowledge is only useful if the tonotopy of the cisternal segment of the vestibulocochlear nerve is known. For exam-

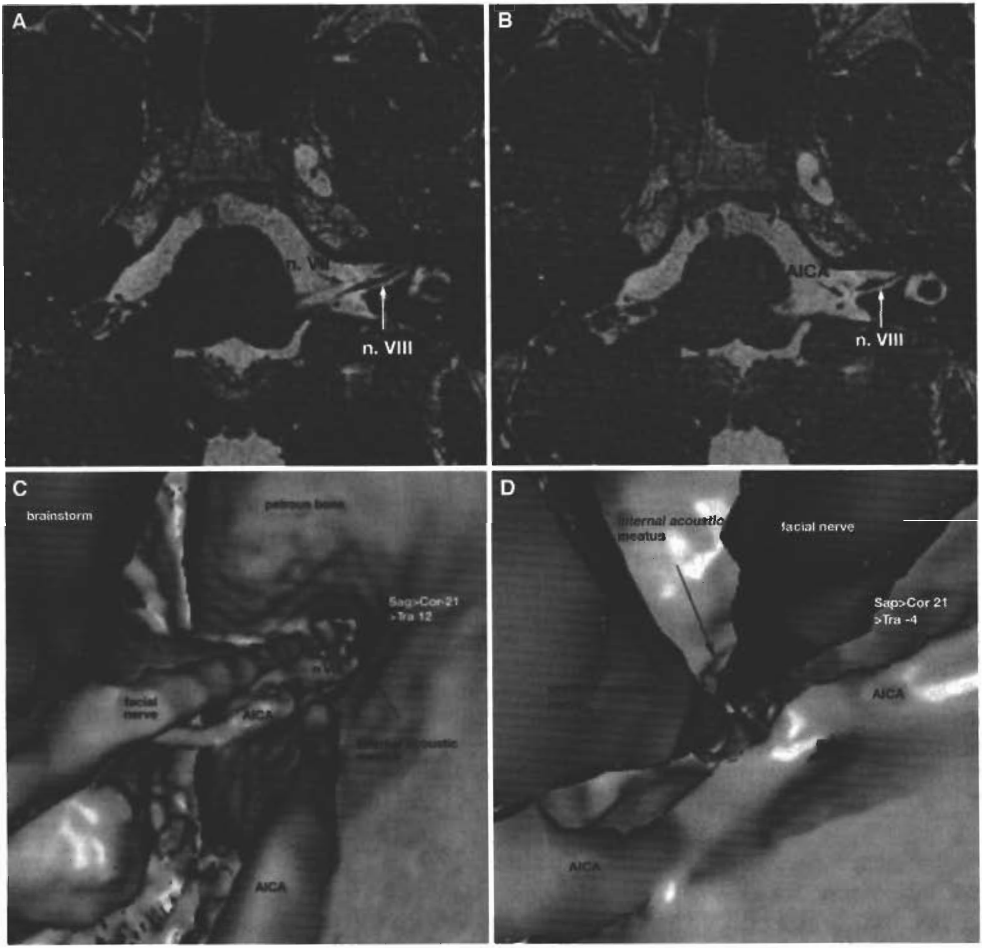

FIGURE 4. A *and* B, *0.6-mm CISS-weighted images. A close vascular-nervous relationship can be seen. Resolution is insufficient to ascertain whether a real vascular compression is present.* C *and* D, *high-resolution (0.6 mm) CISS-weighted images with three-dimensional reconstruction. No vascular compression is present anywhere on the auditory nerve.* AICA, *anteroinferior cerebellar artery;* Sag, *sagittal;* Cor, *coronal;* Tra, *transverse;* n., *cranial nerve.*

ple, a vascular conflict at the posteromedial part of the vestibulocochlear nerve close to the acoustic meatus in the setting of a low-pitch nonpulsatile tinnitus is probably not the cause of the tinnitus. Similarly, a high-pitch nonpulsatile tinnitus and a vascular conflict at the inferior side of the vestibulocochlear nerve close to the brainstem and facial nerve are most likely not related. Thus, knowing the tonotopy might decrease unnecessary operations by decreasing the number of false-positive diagnoses. For this to be successful, however, a more sophisticated imaging technique is required, and ultrathin (0.6 mm) constructive interference in steady state (CISS)-weighted imaging with three-dimensional reconstruction might be the choice for the future, if it can fulfill its promises. The usefulness of such technique is demonstrated in *Figure 4, A* and *B*, which show results from a patient with unilateral tinnitus who was scanned with classical 0.8-mm CISS-weighted images. The MRI scans shown in *Figure 4, A* and *B*, demonstrate the presence of a close vascular-nervous relationship on the side ipsilateral to the side where the patient perceives the tinnitus. However, the resolution is insufficient to be certain whether a real contact is present between nerve and blood vessel. Ultrathin 0.6-mm CISS-weighted images with three-dimensional reconstructions (*Fig. 4, C* and *D*) of the same patient clearly demonstrate that no vascular contact is present anywhere on the auditory nerve. We therefore think that the patient's tinnitus was not caused by a vascular compression.

CONCLUSION

The tonotopic organization of the cisternal segment of the cochlear nerve has an oblique rotatory structure as a result of the rotatory course of the cochlear nerve in the posterior fossa. Low-frequency tones seem to be located at the posterolateral part of the cochlear nerve close to the brainstem; high frequencies are more medial and closer to the internal acoustic meatus, as seen from a retrosigmoid approach. Knowledge of this tonotopic organization of the auditory nerve in its cisternal course might benefit surgeons who perform MVD operations for vestibulocochlear compression syndrome, especially in the treatment of unilateral severe tinnitus.

REFERENCES

1. Arnesen AR, Osen KK: The cochlear nerve in the cat: Topography, cochleotopy, and fiber spectrum. **J Comp Neurol** 178:661–678, 1978.
2. Barker FG, Jannetta PJ, Bissonette DJ, Larkins MV, Jho HD: The long-term outcome of microvascular decompression for trigeminal neuralgia. **N Engl J Med** 334:1077–1083, 1996.
3. Barker FG, Jannetta PJ, Bissonette DJ, Shields PT, Larkins MV: Microvascular decompression for hemifacial spasm. **J Neurosurg** 201–210, 1995.
4. Brugge JF: An overview of central auditory processing, in Popper AN, Fay RR (eds): *The Mammalian Auditory Pathway: Neurophysiology*. New York, Springer-Verlag, 1992, pp 1–33.
5. De Ridder D, Møller A, Verlooy J, Cornelissen M, De Ridder L: Is the root entry/exit zone important in microvascular compression syndromes? **Neurosurgery** 51:427–434, 2002.
6. Devor M: The pathophysiology of damaged peripheral nerves, in Wall PD, Melzack R (eds): *Textbook of Pain*. Edinburgh, Churchill Livingstone, 1994, ed 4, pp 79–100.
7. Devor M, Seltzer Z: Pathophysiology of damaged nerves in relation to chronic pain, in Wall PD, Melzack R (eds): *Textbook of Pain*. Edinburgh, Churchill Livingstone, 1994, ed 4, pp 129–164.
8. Devor M, Govrin-Lippmann R, Rappaport ZH: Mechanism of trigeminal neuralgia: An ultrastructural analysis of trigeminal root specimens obtained during microvascular decompression surgery. **J Neurosurg** 96:532–543, 2002.
9. Felix H, Johnsson LG, Gleeson MJ, de Fraissinette A, Conen V: Morphometric analysis of the cochlear nerve in man. **Acta Otolaryngol (Stockh)** 112:284–287, 1992.
10. Flor H, Elbert T, Knecht S, Wienbruch C, Pantev C, Birbaumer N, Larbig W, Taub E: Phantom-limb pain as a perceptual correlate of cortical reorganization following arm amputation. **Nature** 375:482–484, 1995.
11. Harrison RV, Ibrahim D, Mount RJ: Plasticity of tonotopic maps in auditory midbrain following partial cochlear damage in the developing chinchilla. **Exp Brain Res** 123:449–460, 1998.
12. Harrison RV, Ibrahim D, Stanton SG, Mount RJ: Reorganization of frequency maps in chinchilla auditory midbrain after long-term basal cochlear lesion induced at birth, in Salvi RJ, Henderson B, Fiorino F, Colletti V (eds): *Auditory System Plasticity and Regeneration*. New York, Thieme, 1996, pp 238–255.
13. Jannetta PJ: Outcome after microvascular decompression for typical trigeminal neuralgia, hemifacial spasm, tinnitus, disabling positional vertigo and glossopharyngeal neuralgia. **Clin Neurosurg** 44:331–384, 1996.
14. Jannetta PJ: Selection criteria for the treatment of cranial rhizopathies by microvascular decompression. **Clin Neurosurg** 44:69–78, 1996.
15. Jastreboff PJ: Phantom auditory perception (tinnitus): Mechanisms of generation and perception. **Neurosci Res** 8:221–254, 1990.
16. Kaas JH: Plasticity of sensory and motor maps in adult mammals. **Annu Rev Neurosci** 14:137–167, 1991.
17. Kaltenbach JA: Hyperactivity in the dorsal cochlear nucleus after intense sound exposure and its resemblance to tone-evoked activity: A physiological model for tinnitus. **Hear Res** 140:165–172, 2000.
18. Kaltenbach JA, Meleca RJ, Falzarano PR: Alterations in the tonotopic map of the cochlear nucleus following cochlear damage, in Salvi RJ, Henderson D, Fiorino F, Colletti V (eds): *Auditory System Plasticity and Regeneration*. New York, Thieme Medical Publishers, 1996, pp 317–332.
19. Kim HN, Kim YH, Park IY, Kim GR, Chung IH: Variability of the surgical anatomy of the neurovascular complex of the cerebellopontine angle. **Ann Otol Rhinol Laryngol** 94:288–296, 1990.
20. Lang J: Anatomy of the brainstem and the lower cranial nerves, vessels, and surrounding structures. **Am J Otol** Suppl:1–19, 1985.
21. Leclercq TA, Hill CL, Grisoli F: Retromastoid microsurgical approach to vascular compression of the eighth cranial nerve. **Laryngoscope** 90:1011–1017, 1980.
22. LeDoux JE: Brain mechanisms of emotion and emotional learning. **Curr Opin Neurobiol** 2:191–197, 1992.
23. Lockwood A, Salvi R, Coad M, Towsley M, Wack D, Murphy B: The functional neuroanatomy of tinnitus: Evidence for limbic system links and neural plasticity. **Neurology** 50:114–120, 1998.
24. Makins AE, Nikolopoulos TP, Ludman C, O'Donoghue GM: Is there a correlation between vascular loops and unilateral auditory symptoms? **Laryngoscope** 108:1739–1742, 1998.
25. Matsushima T, Inoue T, Fukui M: Arteries in contact with the cisternal portion of the facial nerve in autopsy cases: Microsurgical anatomy for neurovascular decompression surgery of hemifacial spasm. **Surg Neurol** 34:87–93, 1990.
26. McCabe BF, Gantz BJ: Vascular loop as a cause of incapacitating dizziness. **Am J Otol** 10:117–120, 1989.
27. Melcher JR, Sigalovsky IS, Guinan JJ Jr, Levine RA: Lateralized tinnitus studied with functional magnetic resonance imaging: Abnormal inferior colliculus activation. **J Neurophysiol** 83:1058–1072, 2000.
28. Møller AR: Pathophysiology of tinnitus. **Ann Otol Rhinol Laryngol** 93:39–44, 1984.

29. Møller AR: Cranial nerve dysfunction syndromes: Pathophysiology of microvascular compression, in Barrow DL (ed): *Neurosurgical Topics Book 13: Surgery of Cranial Nerves of the Posterior Fossa*. Park Ridge, AANS, 1993, pp 105–129.
30. Møller AR: Similarities between chronic pain and tinnitus. **Am J Otol** 18:577–585, 1997.
31. Møller AR: Vascular compression of cranial nerves: Part II—Pathophysiology. **Neurol Res** 21:439–443, 1999.
32. Møller AR: Representation of frequency in the auditory system, in *Hearing: Its Physiology and Pathophysiology*. San Diego, Academic Press, 2000, pp 151–179.
33. Møller AR: Hearing, in *Sensory Systems: Anatomy and Physiology*. Amsterdam, Academic Press, 2002, p 347.
34. Møller MB, Møller AR: Audiometric abnormalities in hemifacial spasm. **Audiology** 24:396–405, 1985.
35. Møller AR, Colletti V, Fiorino F: Click evoked responses from the exposed intracranial portion of the eighth nerve during vestibular nerve section: Bipolar and monopolar recordings. **Electroenceph Clin Neurophysiol** 92: 17–29, 1994.
36. Møller AR, Colletti V, Fiorino FG: Neural conduction velocity of the human auditory nerve: Bipolar recordings from the exposed intracranial portion of the eighth nerve during vestibular nerve section. **Electroenceph Clin Neurophysiol** 92:316–320, 1994.
37. Møller MB, Møller AR, Jannetta PJ, Jho HD: Vascular decompression surgery for severe tinnitus: Selection criteria and results. **Laryngoscope** 103: 421–427, 1993.
38. Møller AR, Møller MB, Yokota M: Some forms of tinnitus may involve the extralemniscal auditory pathway. **Laryngoscope** 102:1165–1171, 1992.
39. Mühlnickel W, Elbert T, Taub E, Flor H: Reorganization of auditory cortex in tinnitus. **Proc Natl Acad Sci U S A** 95:10340–10343, 1998.
40. Ouaknine GE: Microsurgical anatomy of the arterial loops in the ponto-cerebellar angle and the internal acoustic meatus, in Samii M, Jannetta PJ (eds): *The Cranial Nerves*. Heidelberg, Springer-Verlag, 1981, pp 378–390.
41. Pantev C, Lutkenhoner B: Magnetoencephalographic studies of functional organization and plasticity of the human auditory cortex. **J Clin Neurophysiol** 17:130–142, 2000.
42. Parnes LS, Shimotakahara SG, Pelz D, Lee D, Fox AJ: Vascular relationships of the vestibulocochlear nerve on magnetic resonance imaging. **Am J Otol** 11:278–281, 1990.
43. Rajan R, Irvine DR: Neuronal responses across cortical field A1 in plasticity induced by peripheral auditory organ damage. **Audiol Neurootol** 3:123–144, 1998.
44. Rauschecker JP: Auditory cortical plasticity: A comparison with other sensory systems. **Trends Neurosci** 22:74–80, 1999.
45. Robertson D, Irvine DR: Plasticity of frequency organization in auditory cortex of guinea pigs with partial unilateral deafness. **J Comp Neurol** 282:456–471, 1989.
46. Rosseau GL, Jannetta PJ, Hirsch B, Møller MB, Møller AR: Restoration of useful hearing after microvascular decompression of the cochlear nerve. **Am J Otol** 14:392–397, 1993.
47. Ryan AF, Woolf NK: Development of tonotopic representation in the Mongolian Gerbil: A 2-deoxyglucose study. **Brain Res** 469:61–70, 1988.
48. Ryu H, Yamamoto S, Sugiyama K, Nishizawa S, Nozue M: Neurovascular compression syndrome of the eighth cranial nerve: Can the site of compression explain the symptoms? **Acta Neurochir (Wien)** 141:495–501, 1999.
49. Ryu H, Yamamoto S, Sugiyama K, Nozue M: Neurovascular compression syndrome of the eighth cranial nerve: What are the most reliable diagnostic signs? **Acta Neurochir (Wien)** 140:1279–1286, 1998.
50. Ryu H, Yamamoto S, Sugiyama K, Uemura K, Nozue M: Neurovascular decompression of the eighth cranial nerve in patients with hemifacial spasm and incidental tinnitus: An alternative way to study tinnitus. **J Neurosurg** 88:232–236, 1998.
51. Sando I: The anatomical interrelationships of the cochlear nerve fibers. **Acta Otolaryngol (Stockh)** 59:417–436, 1965.
52. Schwaber MK, Whetsell WO: Cochleovestibular nerve compression syndrome: Part II—Vestibular nerve histopathology and theory of pathophysiology. **Laryngoscope** 102:1030–1036, 1992.
53. Sen CN, Møller AR: Signs of hemifacial spasm created by chronic periodic stimulation of the facial nerve in the rat. **Exp Neurol** 98:336–349, 1987.
54. Silverstein H, Norrell H, Haberkamp T, McDaniel AB: The unrecognized rotation of the vestibular and cochlear nerves from the labyrinth to the brain stem: Its implications to surgery of the eighth cranial nerve. **Otolaryngol Head Neck Surg** 95:543–549, 1986.
55. Spoendlin H, Schrott A: Analysis of the human auditory nerve. **Hear Res** 43:25–38, 1989.
56. Sunderland S: Microvascular relations and anomalies at the base of the brain. **J Neurol Neurosurg Psychiatry** 11:243–257, 1948.
57. Sunderland S: Cranial nerve injury: Structural and pathophysiological considerations and a classification of nerve injury, in Samii P, Jannetta P (eds): *The Cranial Nerves*. New York, Springer-Verlag, 1981, pp 16–23.
58. Talavage TM, Ledden PJ, Benson RR, Rosen BR, Melcher JR: Frequency-dependent responses exhibited by multiple regions in human auditory cortex. **Hear Res** 150:225–244, 2000.
59. Ter Bruggen JP, Keunen RW, Tijssen CC, Wijnalda D: Octavus nerve neurovascular compression syndrome. **Eur Neurol** 27:82–87, 1987.
60. Tonndorf J: The analogy between tinnitus and pain: A suggestion for a physiological basis of chronic tinnitus. **Hear Res** 28:271–275, 1987.
61. Wessinger CM, VanMeter J, Tian B, Van Lare J, Pekar J, Rauschecker JP: Hierarchical organization of the human auditory cortex revealed by functional magnetic resonance Imaging. **J Cogn Neurosci** 13:1–7, 2001.
62. Williot JF: Auditory system plasticity in the adult C57BL/6J mouse, in Salvi RJ, Henderson B, Fiorino F, Colletti V (eds): *Auditory System Plasticity and Regeneration*. New York, Thieme, 1996, pp 297–316.

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COMMENTS

The effectiveness of microvascular decompression (MVD) for the so-called auditory nerve compression syndromes is still debated, and patients must be selected in a very critical way. Therefore, all contributions aimed at collecting data and consequently improving knowledge in the field are of practical importance. This article is a stimulating work with an intelligent and imaginative design of the study, more than the fruit of sophisticated and costly technologies. The substance of the work has undoubtedly benefited from cross-fertilization thanks to the collaboration of several experts from different horizons.

The authors have described a tonotopic organization in the cisternal portion of the cochlear nerve. Their conclusions were derived from the observation that the offending vascular loop was responsible for a reversible deficit attaining specific frequencies corresponding to the fibers compressed. We made similar observations in the trigeminal roots of patients affected with trigeminal neuralgia who underwent MVD. We found that there were positive correlations between the topography of the neuralgia (i.e., the division or divisions involved) and the site of the neurovascular conflict. V_1 division was predominant when the site of neurovascular conflict was superomedial; V_2, superolateral; and V_3, lateral and/or inferior (2). These findings are concordant with the known somatotopic organization of the cisternal portion of the trigeminal root (1).

Perhaps our main criticism would be the excessive confidence that the authors place in the capacity to predict outcome of MVD of the VIIIth nerve for tinnitus, that is, to make accurate patient selection, on the basis of the type of tinnitus (low or high pitch) and the location of the visible arterial loop on magnetic resonance imaging. As a matter of fact (as actually pointed out by the authors), there are many asymptomatic vascular loops in the cerebellopontine angle, and according to many surgeons' experience (even with recourse to high-resolution magnetic resonance explorations), the reliability of magnetic resonance imaging is still disputable.

We think that it would be hazardous to rely too much on imaging. Other criteria, clinical, electrophysiological, and perhaps also pharmacological, would be most helpful to make patient selection more rigorous.

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1. Gundmundsson K, Rhoton AL Jr, Rushton JG: Detailed anatomy of intracranial portion of the trigeminal nerve. **J Neurosurg** 35:592–600, 1971.
2. Sindou M, Howeidy T, Acevedo G: Anatomical observations during microvascular decompression for idiopathic trigeminal neuralgia (with correlations between topography of pain and site of the neurovascular conflict): Prospective study in a series of 579 patients. **Acta Neurochir (Wien)** 144:1–13, 2002.

De Ridder et al. have studied the frequency-specific hearing improvement after MVD of the vestibulocochlear nerve in patients with vertigo or tinnitus. In 18 of 31 patients analyzed, correlations could be found to the site of nerve compression.

On the basis of their careful observations, the authors conclude a tonotopic organization of the cochlear nerve that corresponds to its rotatory course in the cerebellopontine angle. Furthermore, low frequencies were found to be located close to the brainstem more inferior along the posterior aspect of the cochlear nerve, with high frequencies being located close to the internal acoustic meatus, more superior along the posterior aspect.

This study on functional anatomy is an intriguing approach to the improvement of diagnostic and prognostic criteria for MVD of the VIIIth cranial nerve. It is an important step in the direction of bridging the gap between clinical and neurophysiological data on the one hand and imaging data on the other in patients with vestibulocochlear deficits who may be selected for MVD of the VIIIth nerve. As long as the available imaging techniques alone allow no definite proof of a vascular compression of the nerve, the knowledge of its functional anatomy may help in interpreting the imaging findings.

Although there is still a large degree of unpredictability in these cases because of both the high interindividual variability of the tonotopic organization of the vestibulocochlear nerve and the possibility of compression-induced reorganization, this report adds substantially to the growing pool of information favoring MVD of the VIIIth nerve for selected patients suffering from vestibulocochlear deficits.

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This article by De Ridder et al. documents a continuing exploration of the functional anatomy of the cranial nerves. This information is of preliminary interest and establishes the findings of one group in decompression surgery. As we have found previously, an intimate knowledge of the functional areas of the nerve allows for more precise evaluation and ultimate treatment for cranial nerve disorders of hyperfunction and hypofunction as has been seen in the disabling positional vertigo involving this same nerve as well as the VIIth cranial nerve for the two variations of hemifacial spasm.

We anticipate that additional information and correlation from other clinics will allow for improvement in the success rate for the surgical decompression performed for tinnitus.

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This article represents an interesting and original approach to determine the relationship between tinnitus presumably caused by microvascular compression, the tonotopic organization of the cochlear nerve, and hearing improvement after MVD. The evidence of hearing improvement is correlated with the compression site of the cisternal portion of the cochlear nerve and thus sheds additional light on its tonotopic organization in humans. Although hearing improvement is well documented, this information would have been more specific had the authors used a smaller audiometric step size than the standard 5 dB used for clinical testing, i.e., 3 or 1 dB. This would have allowed the documentation of small but potentially significant changes. The tinnitus experienced by these patients is described only in relatively general terms, as are the nature and extent of postoperative improvement. In this type of study, preoperative and postoperative tinnitus matching (to a pure tone or narrow band of noise) and/or tinnitus masking to determine its intensity and frequency characteristics would have been very informative, and an interesting relationship between the specific nature of tinnitus and hearing improvement along with cochlear nerve compression site could have been established.

The ultimate goal of this study, as stated by the authors, is to use the results to determine diagnostic and prognostic criteria for MVD of the cochlear nerve in patients with tinnitus. The results of the study, however, fall short of this goal. First, the article does not include information about the criteria used to recommend MVD of the cochlear nerve in their patients, and, as stated by the authors, there is evidence that a large number of individuals with vascular compression of the cisternal portion of the cochlear nerve are in fact asymptomatic. Furthermore, as stated, the presence of a loop of the anteroinferior cerebellar artery may be in contact with the VIIIth cranial nerve in 25% of symptomatic patients and 21.4% of asymptomatic patients, as demonstrated by magnetic resonance imaging. It is encouraging that after MVD, 66% of their patients experienced improvement (including complete resolution). The results, however, do not shed sufficient light on differences between the 66% with improved symptoms and the 34% who were unchanged. We may hope that the authors will continue this line of research and implement more specific hearing and tinnitus measures.

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IVLII CASSERII
PLACENTINI
Olim in Patauino Gymnasio Ana:
tomiæ et Chirurgiæ Professoris
celeberrimi
TABVLÆ, ANATOMICÆ LXXIIX,
Omnes nouæ nec ante hac visæ.
DANIEL BVCRETIVS
Vratislauiensis, Philos. et Med. D.
XX quæ deerant suppleuit et omnium
explicationes addidit.
VENETIIS.
Anno MDCXXVII.

***Frontispiece of Casserius'* Tabulae Anatomicae** *(Venice, E. Duechinum, 1627). Giulio Casserius (also called Casserio) (c. 1561–1616) illustrated the vessels at the base of the brain in his work. (Courtesy, Rare Book Room, Norris Medical Library, Keck School of Medicine, University of Southern California, Los Angeles, California.) Also see pages 396, 464, and 499.*