Anatomy of the human cochlear nucleus in relation to auditory brainstem implants

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Abstract— **OBJECTIVE: The performance of auditory brainstem implants is significantly inferior to that of cochlear implants with respect to auditory perceptions in profoundly deaf patients. Inconsistencies in the electrode-tissue-interface may contribute to this issue. The study fills in essential data on the anatomical variability of the human cochlear nucleus complex (CNC) that have never been systematically analyzed before.**

METHODS: The location and the size of 33 CNC (17 right-sided, 16 left-sided) were examined in cross-axial sections of 20 formalin-fixed specimens with the aid of a light microscope. Length, size, width, and the relationship to the intramedullary portion of facial nerve have been assessed for both the ventral (VCN) and dorsal portion (DCN) of the nucleus on either side. All measurements were corrected by a factor of 1.13 (12%) for transverse and 1.21 (17%) for longitudinal shrinkage.

RESULTS: The shape of the cochlear nuclei is complex, creating a distorted X-shaped silhouette in a sagittal view of the brainstem. Mean maximal dimensions (anteroposterior x mediolateral x rostrocaudal; ± standard deviation) obtained for the VCN were 4.59 ± 0.89 x 1.53 ± 0.64 x 3.18 ± 0.69 mm, and 3.42 ± 1.21 x 0.68 ± 0.20 x 1.90 ± 0.66 mm for the DCN. Interindividual differences were highly significant and there was considerable overlap between VCN and DCN in the sagittal plane. While the outer posterolateral surface of the DCN runs almost parallel to the surface of the brainstem in a mean depth of about 0.3 mm, the VCN gradually dives into the depth in the rostroventral direction, ending up at a mean minimum of 7 mm off the surface.

CONCLUSION: The complex morphology of the CNC, its interindividual variability, and its varying location with respect to the surface of the brainstem and outer landmarks constitute a major challenge in designing auditory brainstem implants.

Keywords— **auditory brainstem implant, cochlear nucleus, neural electrode interface, anatomy, landmarks**

I. INTRODUCTION

The anatomy of the cochlear nucleus (CN) as well as its neighboring and landmark anatomical structures have become of interest for auditory brainstem implantation. In addition to the classical surface electrodes placed into the lateral recess of the fourth ventricle since the 1980ies, penetrating brainstem electrodes have now also been implanted to interface the cochlear nuclei with a speech processor in order to partially restore hearing [1].

In an attempt to guide surgical approaches for the purpose of implanting electrodes at this site, a number of authors have described the complex histological structure of the cochlear nucleus complex [3,5,6,11]. While the outline of the ventral and dorsal cochlear nuclei have also been investigated with a few studies designed to measure the size of the nucleus based on surface formations [2,3,8,10], the internal dimensions, the depth, and the orientation of the nuclei inside the human brainstem have not been studied systematically before. Knowledge about these parameters largely stems from individual cases [7]. Surface electrodes for CN stimulation are implanted into a small “tube” that is called the “lateral recess” of the fourth brain ventricle, so that the portion of the CN that can be electrically stimulated is mostly determined by the size of the electrode carrier and the spacing of the electrode contacts. Penetrating electrodes have to be injected into the brainstem tissue itself. Entry point, trajectory and length of electrode shafts are important variable for the efficacy and safety of penetrating auditory brainstem implants (PABI) than for the classical surface implant.

The present study examines size, spatial orientation, and surface depth of the ventral and dorsal cochlear nucleus in histological cross-sections of human brainstem specimens.

II. METHODS

Size and location of 33 CNC (17 right-sided, 16 left-sided) obtained from 20 formalin-fixed specimen taken from autopsies of 11 male and 9 female patients were examined in cross-axial brainstem sections with the aid of a light microscope (Leica®, magnification x2.5, Neubauer ocular scale, resolution 4µm). Mean age of the patients at death was 57.5 (48-83) years. Brain weight varied between 1100g und 1600g (mean 1362g). The brains were fixed in Formalin for at least 6 weeks to balance for swelling and shrinkage. All measurements were corrected by a factor of 1.13 (12%) for transverse and 1.21 (17%) for longitudinal shrinkage caused by histological preparation.

Length, width, and height have been measured for both the ventral (VCN) and dorsal portion (DCN) of the nucleus on either side (Fig. 1, 2). The relationship of the nuclei to the intramedullary portion of facial nerve was determined.

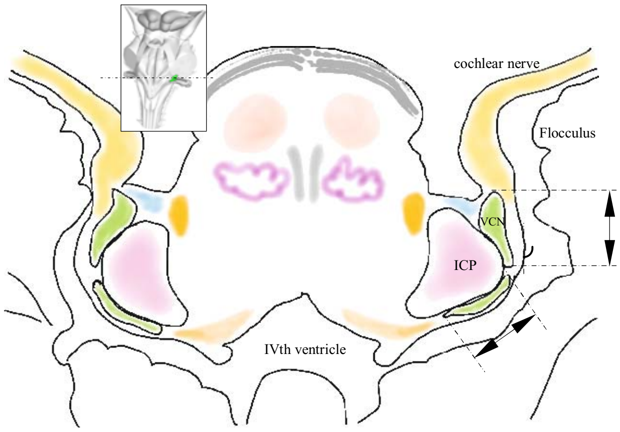

Fig. 1
Longitudinal section of the brainstem at the level of the entry zone of the cochlear nerve. The variable "length" of VCN and DCN is indicated by the arrows. ICP…inferior cerebellar peduncle VCN…ventral cochlea nucleus

The most rostral section of the intramedullary segment of facial nerve was used for an anatomical referencing of the height, i.e. the sagittal extension of the nuclei, (Fig. 2).

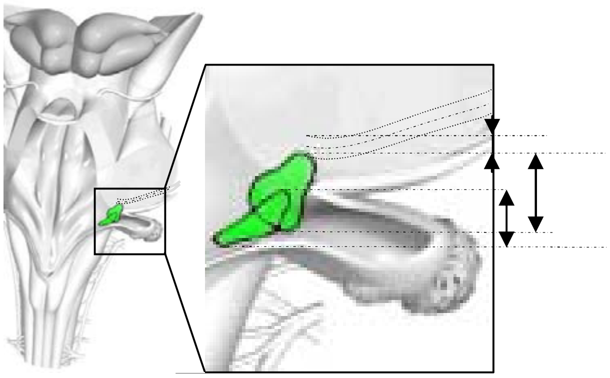

Fig. 2
Coronal section through the brainstem at the level of the cochlear nuclei Arrows indicate the height of the nuclei and the distance to the intramedullary facial nerve. Note the regular anatomical overlap between VCN and DCN. The overall height of the CNC accessible to electrodes therefore is smaller than the combined height of the VCN and DCN.

Data were analyzed using the SPSS PC+ statistical package. Chi-Squares and Kolmogorov-Smirnov tests did not reveal significant derivations of the data from the normal distribution.

A univariate ANOVA was performed for left/right side differences. Pearson correlations have been obtained for grouped variables like diameters of the cochlear nuclei in axial, coronal and sagittal planes.

III. Results

The cochlear nucleus complex has an overall extension of 8.01 x 1.53 x 3.76 mm (length x width x height) in respect to the intrinsic axis of the complex was with standard deviations ranging between 1-2 mm (see Table 1).

Table 1. Mean (± standard deviation) of the maximum measured dimensions in each histological slice of the DCN, VCN, and the complete nucleus (CNC)

	Length	**Width**	**Height**
	anteroposterior	mediolateral	rostrocaudal
DCN	3.42 ± 1.21	0.68 ± 0.20	1.90 ± 0.66
VCN	4.59 ± 0.89	1.53 ± 0.64	3.18 ± 0.69
CNC	**8.01 ± 1.05**	**1.53 ± 0.64**	**3.76 ± 0.89**

While for the DCN maximum length and width fell together at one single level, the VCN was longer in lower section but wider in more superior slices.

There was an inter-individual variability with a factor of 3 between extremes in all data. This is best illustrated by the smallest and largest dimensions that have been encountered (Table 2a&b).

Table 2. Variability of the extension of the human cochlear nucleus

a. Smallest mean maxima of the dimensions of the cochlear nuclei. Because the measurements have been carried out in transverse sections, there is only one composite value per case for the variable "height".

	Length	**Width**	**Height**
	anteroposterior	mediolateral	rostrocaudal
DCN	1.46 ± 1.00	0.29 ± 0.19	0.77
VCN	1.92 ± 1.11	0.78 ± 0.31	2.32
CNC	**3.38 ± 1.05**	**0.78 ± 0.31**	**2.32**

b. Largest mean maxima of the dimensions of the cochlear nuclei

	Length	**Width**	**Height**
	anteroposterior	mediolateral	rostrocaudal
DCN	4.24 ± 1.67	0.81 ± 0.19	3.10
VCN	5.42 ± 1.75	2.10 ± 0.91	4.26
CNC	**9.66 ± 3.42**	**2.10 ± 0.91**	**7.36**

No single CNC has been found to be smallest or largest in ***all*** measured dimensions.

Sizes of the ventral and the dorsal cochlear nuclei correlated well with each other.

Except for the length of the dorsal cochlear nucleus, which has been found slightly greater on the 4.14mm left side (4.14 mm versus 2.80 mm on the right side, F=5.52, p=0.38) there were no significant side differences. To the contrary, most parameters including the distance of the nuclei from the surface (depth) correlated well between right and left sides.

The ventral cochlear nucleus reached its maximum diameter (width) either at the level of the first (most rostral) transverse section of the facial nerve or 320µm below that level. Because the axis of the VCN is obliquely orientated to the sagittal plane, the outer surface of the VCN was buried in a mean depth of at least 7 mm from the surface of the brainstem at this location (Fig. 3).

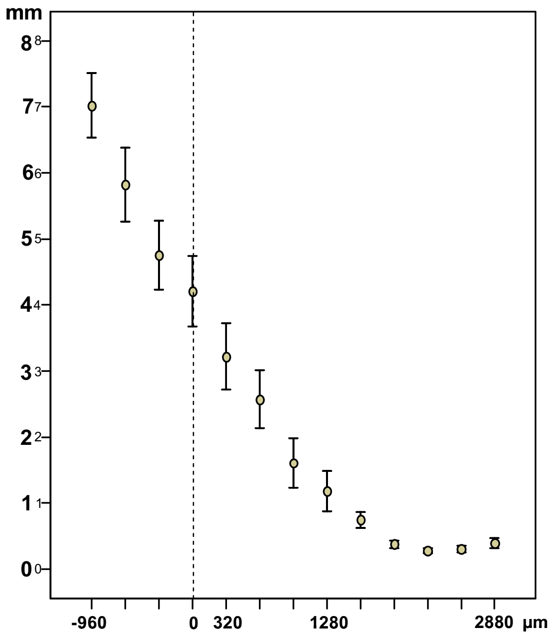

Fig. 3 Minimal surface depth (mean ± standard error) of the VCN The broken line represents the first section of the facial nerve.

The outer surface of the DCN was located almost parallel to the surface of the brainstem with a mean minimal depth of about 0.3 mm (range 0.09 – 0.9 mm).

The spatial orientation of the CNC is most complex. Its shape resembles a distorted X-shaped silhouette in a sagittal view of the brainstem. The upper portion of the VCN is also curving in towards the midline of the medulla oblongata (Fig. 5).

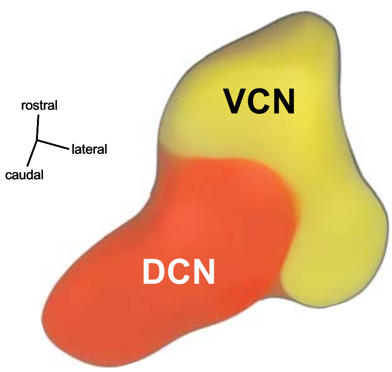

Fig. 5A Three-dimensional rendering of the CNC (lateral view)

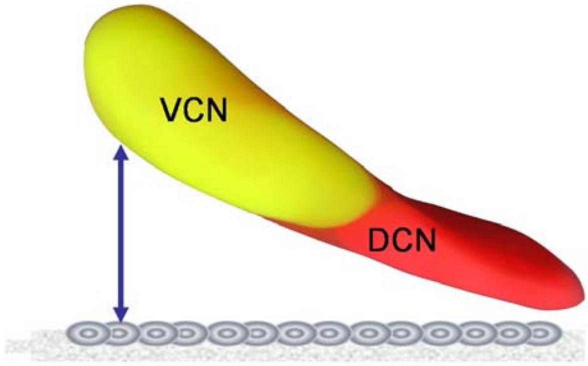

Fig. 5B Three-dimensional rendering of the left CNC (view from above). The arrow indicates the distance of the rostral part of the VCN to a surface electrode (see also Fig. 3).

IV. Discussion

Because of the anatomical overlap of the dorsal and ventral cochlear nuclei in the rostrocaudal axis, the overall "height" (y-axis) of the cochlear nucleus complex (CNC) in this plane is lower than the sum of the height of DNC and VNC combined. Further, because of the inward rotation of the whole complex with respect to the brainstem axis, the projected area for electrode contact at the outer surface does not match the reachable parts of the CNC by electrical stimulation with common surface electrodes. Especially the neurons that are connected to the primary afferents of the cochlear nerve probably do not receive appropriate current to be activated. For a PABI, the entry area for insertion of penetrating electrodes to the cochlear nucleus is no larger than 8 x 3 mm. While these extensions compare relatively well with data from measurements at the surface of the brainstem published in previous studies [2,3,8,10], intrinsic brainstem measurements reveal other dimensions of the challenge to place electrodes inside the nucleus. The diameter DCN is only 1 mm and this part of the CNC is located just under the surface of the brainstem. Electrodes that are longer than 2 mm over a length of about 3.5 mm (the DCN's mean length) will penetrate through the DCN and lose efficacy. Moreover, the upper portion of the VCN can only be reached by electrodes that are as long as 7mm.

Successful surface electrodes reach the CNC mostly at its caudal half, sharply above the exit zone of the ninth cranial nerve, which is located 4.5 mm (2.5-6.5 mm) caudal to the exit zone of the facial nerve [4]. Penetrating electrodes for the upper VCN therefore have to be inserted above the lateral recess in the zenith of the brainstem. The length of the electrode shafts would have to incrementally extend (over a distance of just 3 mm) -

from 2 mm to 7mm. Spacing of the electrodes would have to be narrow – probably as small as 0.75mm which in turn may cause more problems with tissue damage and channel crosstalk.

The PABI implanted by the House Ear Institute in Los Angeles comes close to complying with these constraints and further clinical results should be awaited [1,9].

V. Conclusion

The small dimensions of the CNC, its inter-individual variability, and its varying location with respect to the surface of the brainstem and outer landmarks will continue to constitute a major challenge at the electrode-tissue-interface for these implants.

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