Representation of the Cochlea in the Neocortex of Guinea Pigs*

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Summary. By recording unit clusters and local evoked responses in the auditory cortex of guinea pigs the cortical representation of best frequencies was studied. In penetrations vertical to the cortical surface best frequencies were similar. Parallel to the cortical surface, however, different frequencies were found in the antero-posterior direction, whereas medio-laterally best frequencies usually remained in the same range (isofrequency stripes). Two auditory cortical fields could be distinguished, which are tonotopically organized. With increasing sound intensity the cortical response field for a given frequency and thus the frequency overlap increased. All along the isofrequency stripes in the medio-lateral direction, the stimulation of the contralateral ear produces larger responses than the same stimulus delivered to the ipsilateral ear.

Key words: Auditory cortex – Cochlear representation – Tonotopy – Guinea pig

Introduction

After early pioneering studies regarding cortical localization of auditory functions (Kornmüller, 1937) there have been several attempts to study the organization of cochlear representation in the neocortex (Woolsey and Walzl, 1942; Tunturi, 1950; Hind, 1953; Evans et al., 1965; Goldstein et al., 1970). Most investigators now agree that a general tendency of orderly cochlear representation according to frequency exists in at least one cortical area. The precision of this tonotopy, however, is still controversial (Goldstein and Abeles, 1975). Recently Merzenich et al. (1975) have presented comparative physiological data which demonstrate a distinct cochlear representation in the neocortex of several species (Merzenich et al., 1975; Merzenich et al., 1976; Brugge and Merzenich, 1973). The present work was undertaken in order to extend these studies to include guinea pigs, a species much used for peripheral auditory physiology (Evans, 1970, 1972; Goldstein and Mundie, 1971), but as

yet little used for investigation of corresponding central sensory structures (Zeigler, 1964; Walloch, 1971).

Methods

Eighteen guinea pigs were used for the experiments. They were anaesthetized with urethane-methomidat-HCL (1 g/kg and 2 mg/kg, respectively) and a headholder was mounted with screws and dental cement to the skull. The temporal cortex was exposed and covered with warm mineral oil.

Stimulation

The sound signals were applied monaurally by means of a headphone (Sennheiser, HD 44) or binaurally with a loudspeaker (Isonetta) from the left or from the right side. The sound pressure level was reduced by means of an attenuator (Hewlett-Packard) and was measured in relative magnitudes. Best frequencies wer determined by reducing the sound pressure and then sweeping in frequency from 0–30 kHz until only a narrow frequency range was effective in eliciting a response.

Recording

Low impedance glass pipettes or glass insulated tungsten wires were used. Multiple unitary discharges on top of evoked potentials or evoked potentials alone were recorded. Prior to recording, a picture of the cortical surface was taken in order to mark on it all the penetrations. A number was assigned to each penetration and best frequencies noted. At the end of the experiment formalin was applied locally to preserve the vascularization pattern of the recording site. Sometimes, after numerous penetrations into a relatively small cortical surface area, a brain edema developed. Even though recordings under these conditions usually were well in line with the results obtained earlier, an experiment was terminated as soon as the response character changed and stable unit cluster recordings could not be recorded any more. Another reason for having to terminate an experiment prematurely was an accidental puncture of an artery, for instance.

Evaluation of Data

Pictures of the perfused brains were taken from a lateral angle of 40 degrees. The vascular patterns in vivo and after perfusion were matched and the penetrations and best frequencies were transferred onto a picture of the cortical surface in order to determine the position of the auditory fields in relation to the whole brain.

Results

Vertical and horizontal arrangement of best frequencies: During a single penetration the best frequencies were determined at different depths. The best frequency is – by definition – capable of evoking a response at lower sound pressure levels than other frequencies. Little variation of best frequencies during a penetration normal to the cortical surface was seen. In some penetrations a systematic trend from higher to lower (or vice versa) frequencies existed, but was probably due to an oblique direction of the electrode. At a depth of about 500 micron the responsiveness was best and routinely recordings were obtained at this level.
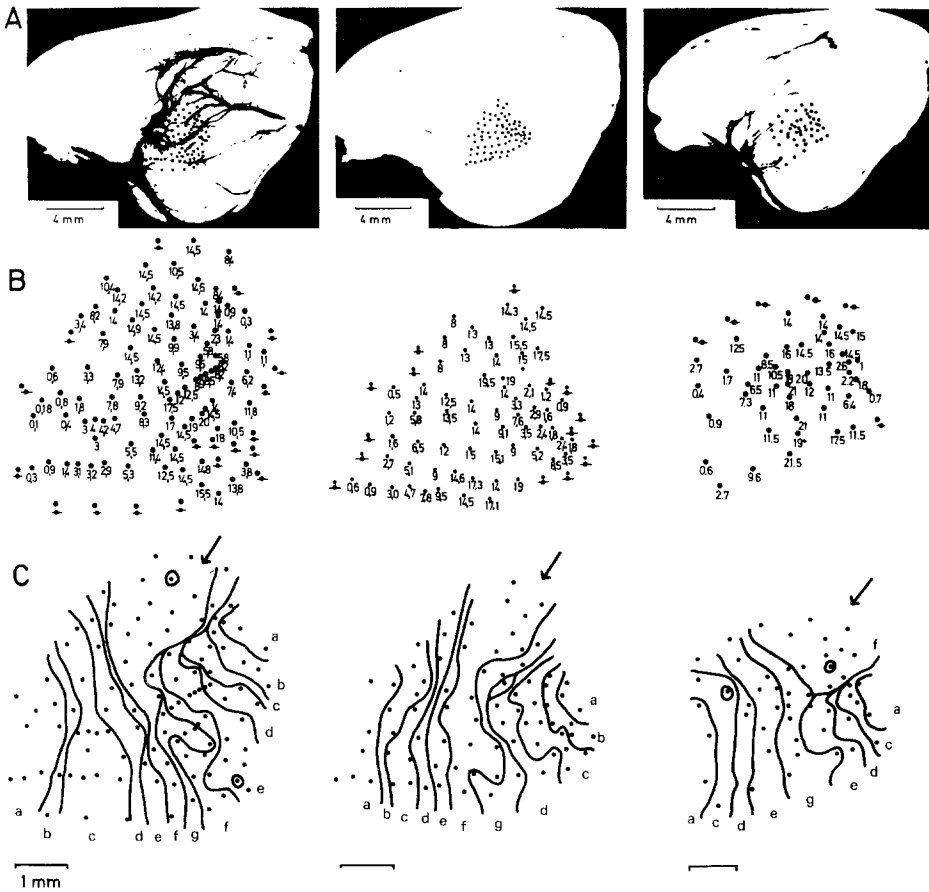
Fig. 1. Three frequency mappings of the auditory cortex of guinea pigs. **A** Penetrations shown in relation to the shape of the whole brain. **B** best frequencies in kHz for the same penetrations. Locations, where no acoustic response could be obtained are also indicated. **C** Ranges of best frequencies between 0 and 1 kHz (a); 1 and 2 kHz (b); 2 and 6 kHz (c); 6 and 8.5 kHz (d); 8.5 and 12.5 kHz (e); 12.5 and 15.5 kHz (f) and 15.5 and 28 kHz (g) are separated by black lines. Note the relatively large representation of 12.5–15.5 kHz medially between area I and arrea II (arrows)

Along the cortical surface frequencies were generally not similar and had characteristic distributions. Cortical frequency maps of three animals are shown in Figure 1. The location of penetrations (black dots) are shown relative to the whole brain (A) and corresponding best frequencies for each penetration are given (B, C). Two regions on each brain show penetrations lined up according to descending or ascending best frequencies. In the larger region (lying anterior, henceforth called area I) low frequencies are represented anteriorly, high frequencies posteriorly. In the smaller area (lying posterior, henceforth called area II) the gradient from low to high frequencies points in the anterior direction. Medially the border of these two areas could not clearly be
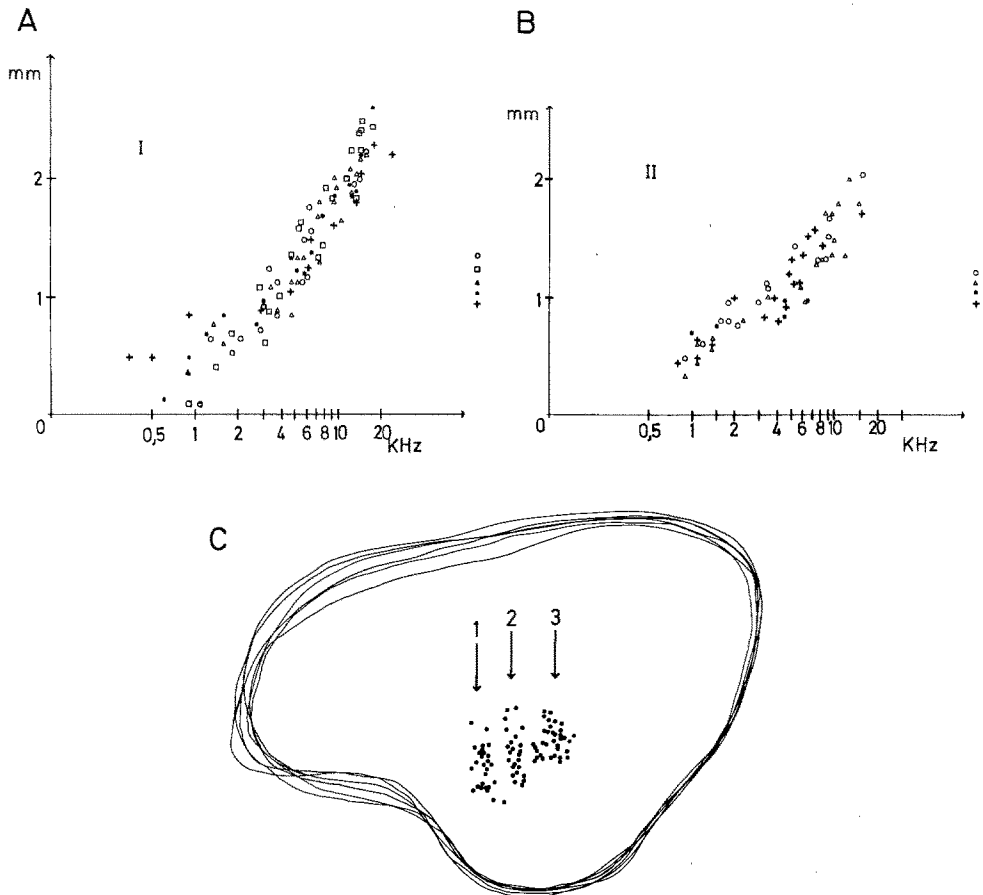
Fig. 2. Distances along the surface of the auditory cortex plotted as a function of best frequency. Each symbol stands for one animal. **A** penetrations within area I, **B** penetrations within area II. In spite of the considerable scatter the slope of the function for area I seems to be steeper than that for area II. **C** Penetrations with best frequencies from 0–2 kHz and 8–12 kHz selected in six animals and photographically superimposed. Arrow 1: frequencies from 0–2 kHz in area I. Arrow 2: frequencies from 8–12 kHz in area I. Arrow 3: both frequencies in area II.

determined. It was clear, however, that no best frequencies of the lower (0–8 kHz) and higher (15.5–28 kHz) range were represented in the medio-posterior part of auditory cortex. The medium frequency range (12.5–15.5 kHz, f in Fig. 1C) therefore occupies a relatively large area of cortex (Fig. 1, arrows). In this area, however, as well as between area I and II, occasionally two or more frequencies were represented at the same spot. Therefore in these cases the best frequency was not the only frequency-maximum seen.

By visual inspection of best frequency distributions on cortical surfaces (for instance Fig. 1) it was found that many best frequency positions did not fit well with their neighbouring ones. Their frequency either was not in line with the
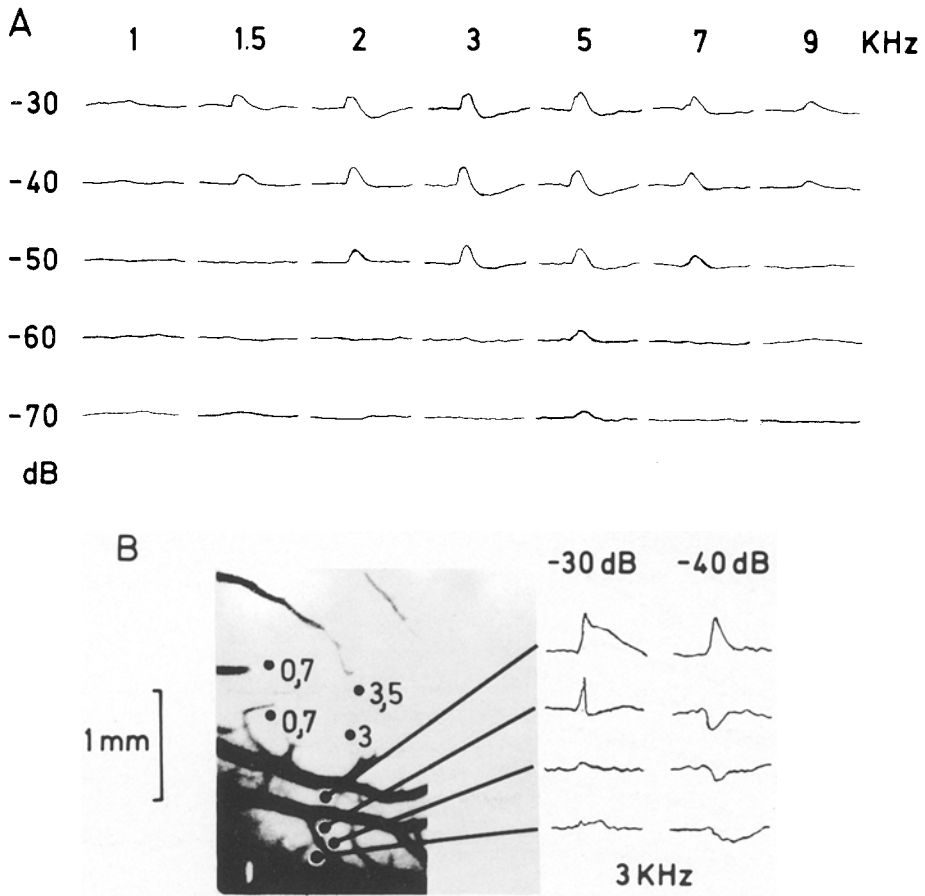
Fig. 3. A Evoked potentials at a given cortical recording site for different frequencies and intensities. The relative attenuation of the sound pressure level is indicated. **B** Evoked potentials recorded from four locations in the cortex, as indicated. Note that the amplitude of the potential decreases when leaving the auditory cortex. All potentials in this and the following figure are averages from twenty single responses

cochleotopic gradient or not – perpendicular to that – with the iso-frequency strip. This scatter is demonstrated in Fig. 2, where the best frequency is plotted as a function of distance along the cortical surface for several animals. By rough eye fitting the gradient in area I is about 0.63 mm distance per octave (Fig. 2A) and in area II is about 0.36 mm distance per octave (Fig. 2B).

Variability of location of the auditory cortex between animals: Between animals considerable variations of the cortical vascularization pattern and of the gyration between temporal and frontal lobe existed. The location of the auditory cortex on the lateral surface of the brain varied only little, however. From six experiments the penetrations with best frequencies between 0 and 2 kHz and 8 and 12 kHz were selected. The photographic pictures of the brains with markings of these penetrations were superimposed by aligning the posterior and
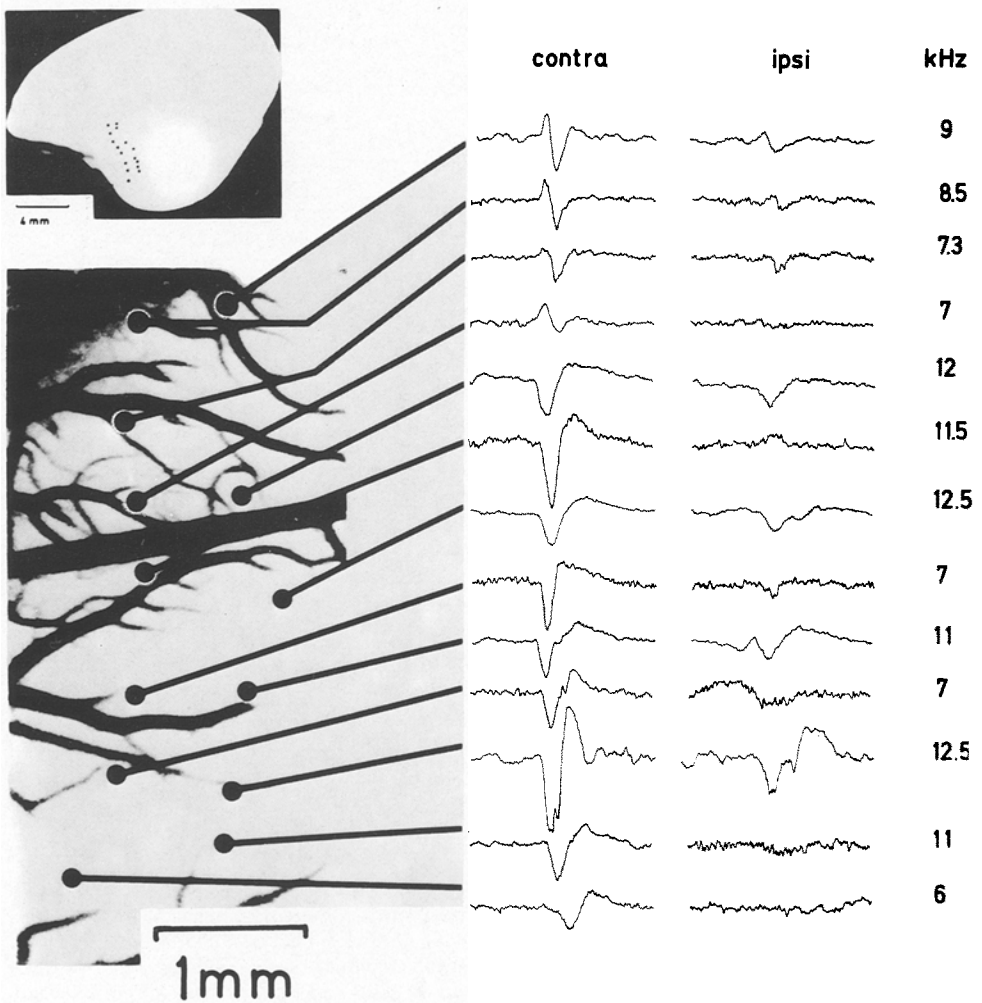
Fig. 4. Binaural input to the cortex along an iso-frequency stripe. On the upper left: penetrations in relation to the shape of the whole brain. Below: penetrations at higher magnification superimposed on the cortical surface. For each penetration the averaged response from 20 stimulus presentations is shown to ipsilateral (ipsi) and contralateral (contra) stimulation. Best frequency for each penetration is given in addition. Sound pressure level was the same for ipsilateral and contralateral stimulation and was adjusted to be about 20 dB above threshold for contralateral stimulation. Note that in all penetrations, regardless whether lying medially or laterally on the iso-frequency strip, the contralateral stimulus is far more effective than the ipsilateral one

basal circumference (Fig. 2C). The groups of points in the 0–2 kHz range (arrow 1) and in the 8–12 kHz range (arrow 2) are well separated. In area II the points of both ranges overlapped (arrow 3).

The threshold nature of the tonotopic representation: With increasing sound intensity, the overlap of frequency representation increased and the tonotopic organization became les clear (Fig. 3A). At increasing sound intensities

neighbouring frequencies could also elicit a response, and at 30–40 dB above threshold frequencies from 1.5–9 kHz were able to elicit a response at a point with 5 kHz best frequency in area I. Such a range of almost three octaves corresponds to a distance of about 1.5 mm on the cortical surface. Current spread seems not to be the only reason for this dispersion, since when leaving the auditory cortex laterally in successive penetrations, the evoked response at the best frequency disappears within 0.5 mm or so (Fig. 3B).

Contralateral aural dominance along the isofrequency stripes: In four animals successive penetrations were made in the medio-lateral direction and it was tested, whether or not the relative input from both ears changed along the iso-frequency stripe. The stimulus was presented from the right or from the left side at an intensity 20 dB above threshold for stimulation of the contralateral ear. In Figure 4 the results of such an experiment are shown. Penetrations had best frequencies in the 6–9 kHz and in the 11–12.5 kHz range. Along the entire isofrequency stripe, stimulation of the contralateral ear (contra) produced a much larger evoked potential than stimulation of the ipsilateral ear (ipsi). There was no significant change of the aural dominance pattern along the isofrequency stripes. It can not be ruled out, however, that other parameters might change along the isofrequency stripes.

Discussion

The arrangement of the auditory cortex of guinea pigs seems to be similar to that of other animals (Tunturi, 1950; Brugge and Merzenich, 1973; Merzenich et al., 1975; Merzenich et al., 1976): One large tonotopically organized field (area I) and a neighbouring smaller one with a reversed frequency gradient (area II) could be demonstrated. In the guinea pig, like in the grey squirrel, low frequencies are represented anteriorly in area I, and in the guinea pig's area II they are represented postero-medially. This distribution is different from that in the cat, where high frequencies in the primary projection area are reported to be represented anteriorly (Merzenich et al., 1975).

Some of the penetrations have best frequencies which do not fit into this scheme. Moreover, among the best frequency penetrations arranged tonotopically, a considerable scatter exists (Fig. 2). This is partly, but not entirely, due to the limited measuring accuracy. Cortical representation of frequencies above 20 kHz was found to be relatively restricted, even though a considerable proportion of the basilar membrane is dedicated to resolving frequencies above 20 kHz. Whether or not this is a phenomenon analogous to the disproportionate cochlear representation described by Suga (1976) still has to be determined.

From the experiments with alternating binaural stimulation it was found that along the whole length of the iso-frequency stripe the stimulation of the contralateral ear was more effective than stimulation of the ipsilateral one. This leaves one question unanswered: Why does a *stripe* of cortex represent a *point* in the cochlea? For the investigation of absolute thresholds between the two ears or for studying the sensitivity also to other sound directions than left or right,

recordings of single cells seem to be necessary to reveal some possible functional changes along the isofrequency stripes.

A broadening of tuning curves at suprathreshold sound intensities is seen already in auditory nerve fibres. As a consequence, an increasing frequency overlap is seen also in the cortex with increasing sound intensity. While a *cochleotopic* cortical representation might exist also at higher sound intensities, a *tonotopic* organization is therefore present only under stimulus-threshold conditions. Since complex acoustic signals, which have to be analyzed by the system, usually are of suprathreshold intensity, a strict separation of its frequency components on the cortical surface may not be expected. Organization according to frequency, therefore, may be only one, perhaps not a very important, principle of functional cortical organization.

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