Marginal Shell of the Anteroventral Cochlear Nucleus: Single-Unit Response Properties in the Unanesthetized Decerebrate Cat

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The AVCN marginal shell receives inputs from the following nonauditory sources: the primary vestibular afferents (Burian and Gstoettner 1988; Kevetter and Perachio 1989), putative second-order vestibular neurons in the vestibular nerve root (Zhao et al. 1995), and somatosensory brain stem nuclei (Itoh et al. 1987; Weinberg and Rustioni 1987). The central core of the AVCN, in contrast, has not been observed to receive any such nonauditory inputs.

Physiological characteristics of marginal shell neurons are yet to be established. Only limited physiological information has been reported for the marginal shell (Bourk 1976; Rose 1960). Although the marginal shell is a unique area of the CN regarding morphology and inputs, there has been no systematic physiological study of this area to our knowledge.

The main hypothesis underlying the present study is that the marginal shell and central core of the AVCN are physiologically different. The goals of the present study are 1) to characterize the physiological properties of single units that are histologically verified to be in the AVCN marginal shell and 2) to compare and contrast the above results with those from the central core of the AVCN in the same animals evaluating the above hypothesis. Observations from the
acoustically not-/weakly driven units of the AVCN marginal shell were described in Ghoshal and Kim (1996a), and an early part of the observations from the acoustically well-driven units of the AVCN marginal shell was described in Ghoshal and Kim (1996b).

METHODS

Animal preparation and unit recording

The procedures of the present study were approved by the University of Connecticut Health Center Animal Care Committee. We used 17 young cats weighing between 1.8 and 2.5 kg obtained from commercial breeders. The cats were sedated initially by intramuscular injection of ketamine (60 mg/kg) usually followed by a supplemental ketamine injection (20% of full dose). Anesthesia was subsequently maintained with halothane gas (0.4–0.8%) mixed with O₂ and N₂O gas (2 l/min each). The cats were also initially injected with atropine (0.047 mg/kg) to reduce congestion of fluid in the respiratory tract.

In some cats, tracheostomy was performed to enable us to clean the trachea when needed and maintain stable respiration throughout the recording procedure. The right middle cranial fossa was opened and a part of the right occipital and temporal lobes was aspirated to expose the midbrain. Decerebration was performed by completely sectioning the brain stem between the superior and inferior colliculi. After decerebration, all anesthetic was discontinued throughout the recording procedure. Fluid containing 5% dextrose and 0.2% sodium chloride was injected through an intravenous catheter at a rate of 0.25 ml/min throughout the duration of the experiment.

The left bulla of the cat was exposed and a thin ventilation tube was inserted into a posterosdoral part of the bulla to avoid negative pressure buildup in the middle ear of the animal. The left posterior fossa was opened. Either we aspirated the left cerebellum exposing the surface of the left CN or we kept the cerebellum intact and accessed the CN with an electrode penetrating through the cerebellum overlying the CN.

Stimulus and data acquisition system

The acoustic signals were generated with a dynamic earphone (Beyer DT 48). We kept the outer and middle ears intact except for placement of a thin ventilation tube in the bulla as noted above, and the acoustic coupler was positioned in the center of the concha in an open system (Kim et al. 1991). For wideband noise, the electric signal applied to the earphone was a Gaussian white noise having a bandwidth of 50 kHz. The sound pressure level at the center of the concha in a typical animal produced with sinusoids at 0 dB attenuation was 111 ± 21 dB SPL re 20 μPa for a frequency range of 0.1–50 kHz. The stimulus signals were presented with a Digital Stimulus System (Medical Electronics Laboratory, University of Wisconsin) under the control of a computer (Digital Equipment, Micro PDP-11). Complete records of spike discharge times and related stimulus markers were stored in the computer files that were subsequently used to compute various histograms and response measures (Kim et al. 1991).

Physiological characterization and marking of the units

In each electrode penetration, a sharp transient and a large negative shift in the recorded voltage signal was used as an estimate of the lateral surface of the AVCN. Within a short distance (0–300 μm), a background response to auditory stimulus was usually encountered. The ventromedial border of the AVCN was estimated to be the location at which the background response to auditory stimulus disappeared and did not reappear as the electrode penetrated further into the tissue.

As the electrode was advanced through the tissue, a frequency-modulated sinusoidal audio search stimulus with a triangular frequency sweep between 0 and 50 kHz was used with a modulation repetition period of 2 s. For each unit, response to the frequency-modulated stimulus provided an approximate estimate of the unit’s characteristic frequency (CF), i.e., the stimulus frequency to which a unit is most sensitive. Additionally, the following responses were obtained to characterize each unit; unless otherwise stated, we used tone bursts and noise bursts 200 ms in duration, with 5-ms rise/fall time with a raised-cosine envelope and 1-s repetition period:

1) SR representing spontaneous discharges sampled for 20 s without any acoustic stimulation;
2) the response areas representing responses to tone bursts presented at various frequencies at constant levels, typically 0–90 dB SPL; this was used to determine the CF and excitatory-inhibitory area (EIA) type of the unit;
3) rate-level functions to pure tone at CF over −15 to 100 dB SPL in 5-dB steps and rate-level functions to wideband noise over 0–90 dB SPL (overall root-mean-square level) in 5-dB steps; and 4) poststimulus time histogram (PSTH) and other response measures to tone bursts, typically at 60 dB SPL, 50-ms duration, 500-ms repetition period, and 60 repetitions.

Marker-filled micropipettes of impedances 10–50 MΩ were used to mark iontophoretically the location of the single-unit recording site by applying a current of 5-nA square pulses 200 ms in duration with a 50% duty cycle for 10–45 min. We used the following markers: 1) a mixture of 10% biotinylated dextran amine (BDA) and 10% dextran, tetramethylrhodamine (DTMR), 2) a mixture of 10% BDA and 10% dextran, fluorescein (DFL), and 3) 10% horseradish peroxidase (HRP). All of the markers were dissolved in 0.5 M potassium acetate (or 0.5 M sodium chloride) and Trizma Buffer (pH 7.5). Usually, one or two additional spots were marked in deeper regions along the same penetration. In every case, the recording depth of each unit was noted. Each marker was used to mark the positions in only one penetration.

Recording of spike waveforms

We recorded entire waveforms of the spike discharges of each single unit during data acquisition with the use of a digital audio tape recorder (Sony, DAT 59ES). Thus the recorded analog waveforms of the spikes allowed us to ascertain the quality and reliability of discriminating single-unit spikes from the background noise. This was particularly important at high stimulus levels, where stimulus artifacts or synchronized compound neural potentials may contaminate the quality of single-unit spike triggering.

Histology and localization of the units

After the completion of the experiment, the cats were transcardially perfused with a fixative of 2% paraformaldehyde and 1% glutaraldehyde. The tissue was embedded in gelatin and sectioned in a transverse plane at 60- to 70-μm thickness. Fluorescence microscopy was used to distinguish the BDA/DTMR and BDA/DFL spots. Tissue was processed for HRP with the use of the tetramethylbenzidine procedure (Mesulam 1982) followed by diaminobenzidine (DAB) without metal intensification to stabilize the reaction, and, for BDA, with the use of the avidin-biotin complex peroxidase reaction followed by the metal-intensified DAB procedure (Veeman et al. 1992). The reaction product for HRP was reddish-brown and that of BDA was grayish-black, and the reaction products were distinguishable. Each section was usually Nissl stained to delineate the cytoarchitectonic areas of the AVCN (Brawer et al. 1974). The amount of tissue shrinkage caused by the histological processing was estimated by comparing the distance between two spots in histological sections with that noted during recording.

For electrode penetrations with visible marking of single-unit
Subgroups of units based on maximum driven rates

Some of the AVCN marginal shell units were found to be not driven or weakly driven by acoustic stimuli (Ghoshal and Kim 1996a), whereas others were well driven. Because the not-driven units were detected only by their spontaneous activities, our study may have systematically missed not-driven spontaneously inactive units if they exist in the AVCN marginal shell. Driven rate was defined as the discharge rate to a stimulus minus the background rate. We subdivided the AVCN shell units into four categories on the basis of maximum driven rates produced by acoustic stimuli: strongly driven, moderately driven, weakly driven, and not driven, with the magnitude of maximum driven rates of >65, 30–65, 5–30, and 0–5 spikes/s, respectively. We refer to the strongly driven and moderately driven units together as the well-driven units. In the present paper we address the acoustically well-driven AVCN marginal shell units and compare them with the AVCN central core units.

Dynamic range

The dynamic range was defined to be the range of the stimulus level at which the driven rate increased monotonically. For the purpose of comparing the rate-level functions of different units exhibiting different maximum driven rates, we often plotted the driven rate as normalized with respect to the maximum driven rate. For saturated rate-level functions, the two ends of the dynamic range corresponded to driven rates of 5 and 95% of the maximum driven rate, or equivalently, to normalized driven rates of 0.05 and 0.95; such examples can be seen in Figs. 2c, 5b, and 6, c–f. When the normalized rate-level function had a positive slope ±0.006/ dB at high levels, the high end corresponded to the normalized driven rate of 1.0; such examples can be seen in Fig. 5, c and d. When the function was nonmonotonic, the dynamic range was defined to correspond to the widest portion of the function, which monotonically increases with increasing level; such examples can be seen in Figs. 2d and 5, a and f.

Results

Physiological characteristics

The waveform of single-unit spike discharges of a typical AVCN marginal shell unit is shown in Fig. 1. It demonstrates that one can record in the AVCN marginal shell large single-unit spikes that can be clearly discriminated above the background noise even at high stimulus levels, e.g., 90 dB SPL wideband noise as shown for this example. Physiological properties (CF, SR, etc.) of each shell unit presented in this and other figures are listed in Table 1.

Physiological response characteristics of a sample AVCN shell unit are shown in Fig. 2, regarding the response area (Fig. 2a), PSTH (Fig. 2b), and rate-level functions to pure tones at CF and to wideband noise (Fig. 2, c and d). In Fig. 2 and other similar figures displaying response areas and rate-level functions, the data points were fitted with smoothing spline functions (The Mathworks, MATLAB). The response area had a well-defined excitatory area and some inhibitory areas (corresponding to negative values of driven rate) surrounding the excitatory area. The PSTH was of a pause-build type. (Note: we refer to the pauser and buildup types combined as the pause-build type.) The rate-level function to pure tones at CF exhibited a monotonic rise from ~0 to ~90 dB SPL with little saturation even at the highest level tested, 95 dB SPL. The maximum driven rate to tone (\(M_T\)) was ~100 spikes/s. The rate-level function to wideband noise exhibited similar characteristics, with a steady rise from ~5 to 80 dB SPL (overall root-mean-square noise level) with a slight decline beyond 80 dB SPL. The maximum driven rate to noise (\(M_N\)) was also ~100 spikes/s. This
The location of each of these units was a dorsolateral part of the anteroventral cochlear nucleus (AVCN) marginal shell except for units Q65-27 and S04-17. The latter units were located in a ventromedial part of the AVCN marginal shell. The units are arranged in the order of their appearance in the text. CF, characteristic frequency; SR, spontaneous rate; PSTH, poststimulus time histogram; EIA, excitatory-inhibitory area; MT, maximum driven rate to tones; MN, maximum driven rate to noise; TT, threshold to pure tones at CF; TN, threshold to noise; DRT, dynamic range with tones; DRN, dynamic range with noise; on-L, onset excitatory response followed by low-level sustained excitatory response; unus., unusual; PB, pause-build; PL, primary-like; on-C, onset-chopper; Ph-L, phase-locked; on-inh, onset excitatory response followed by inhibitory response. * Threshold corresponded to inhibitory response with driven rate of 0 spikes/s. ‡ Variables were difficult to determine.

Maximum driven rates

Figure 3 shows distributions of the MT and MN for the AVCN shell (a, c, and e) and core (b, d, and f) populations. The shell population exhibited wide distributions of MT and MN (Fig. 3, a and c). MT or MN ranged from zero to ~350 spikes/s. The short line segments at 30 and 65 spikes/s in Fig. 3, a–d, represent the borders among the weakly, moderately, and strongly driven units. More than two thirds of the AVCN marginal shell units belonged to the well-driven category, i.e., the moderately and strongly driven categories combined. The distributions of MT and MN of the AVCN core population (Fig. 3, b and d) were markedly different from those of the shell population. The most prominent difference was that the core population were essentially all well-driven units for both tones and noise, whereas the shell population included a substantial portion of weakly not-driven units. The distribution of MT was approximately unimodal with a peak at 230 spikes/s for the core population (Fig. 3b) in contrast to one skewed toward zero for the shell population (Fig. 3a). An analogueous difference was also present between the two distributions of MN (Fig. 3c and d). Fisher’s exact test (e.g., Rosner 1986) was performed to determine whether the differences between the shell and core neural populations were significant. The test result indicated that the differences were highly significant (P < 0.001) regarding both MT and MN.
shell (a, c, and e) and core (b, d, and f) populations. The thresholds represented here corresponded to the stimulus level required to produce a driven rate of 10 spikes/s (Liberman 1978). The rightmost bins in Fig. 4, a and c, represents shell units that were not driven acoustically even at ≥80 dB SPL. Regarding the thresholds to tones and noise, the main differences between the two neural populations were that the threshold distributions were narrower among the core population than among the shell population. For a large majority of the core units, thresholds to tones and noise were <30 and 50 dB SPL, respectively. In contrast, thresholds of the shell units were widely distributed; their thresholds to tones ranged from −20 to 70 dB SPL and tended to have a bimodal distribution, with >50% of them lying above 50 dB SPL. Fisher’s exact test indicated that the differences between the two populations were highly significant regarding the thresholds to tones (P ≤ 0.001) and to noise (P = 0.0015).

Figure 4, e and f, shows distributions of \( T_{ThN} - T_{ThT} \) among the shell units (Fig. 4e) and core units (Fig. 4f). In Fig. 4e, the weakly/not-driven shell units were excluded because their thresholds could not be well specified. Among the core units (Fig. 4f), the distribution of \( T_{ThN} - T_{ThT} \) was unimodal with a mode at +15 dB, indicating that noise thresholds of

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**Figure 3.** a–d: distributions of maximum driven rate to pure tones at CF (\( M_{ThT} \)) and to wideband noise (\( M_{ThN} \)) for the AVCN marginal shell (a and c) and central core (b and d) populations. e and f: distributions of the ratio \( M_{ThN} / M_{ThT} \) for the marginal shell and central core populations, respectively. Short dashes in a–d, at 30 and 65 spikes/s: borders between the weakly driven, moderately driven, and strongly driven units.

Figure 3, e and f, shows the distributions of the ratio \( M_{ThN} / M_{ThT} \) among the shell and core populations, respectively. Figure 3e includes the well-driven shell units but excludes the weakly/not-driven shell units because taking ratios of two numbers both near zero yields spurious results. The distribution of \( M_{ThN} / M_{ThT} \) among the core units was centered around 0.75, indicating that most of the units tended to exhibit a lower \( M_{ThN} \) than to \( M_{ThT} \). In contrast, a more substantial part of the shell units (45%) exhibited \( M_{ThN}/M_{ThT} > 1 \), corresponding to a higher \( M_{ThN} \) than \( M_{ThT} \). Another important difference between the two distributions is the presence of units that were not driven by noise but strongly driven by tones (i.e., \( M_{ThN}/M_{ThT} \) near 0) in the shell population and the absence of such units in the core population. The behavior of \( M_{ThN}/M_{ThT} \) being near zero will be discussed later in the context of EIA types. An implication of \( M_{ThN}/M_{ThT} > 1 \) about integration over a wide bandwidth will be addressed in the DISCUSSION. Fisher’s exact test indicated that the difference between the two neural populations regarding \( M_{ThN}/M_{ThT} \) was significant (\( P = 0.0045 \)).

**Thresholds**

Figure 4 shows the distributions of the thresholds to pure tones at CF (\( T_{ThT} \)) and to wideband noise (\( T_{ThN} \)) among AVCN

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**Figure 4.** a–d: distributions of threshold to pure tones at CF (\( T_{ThT} \)) and to wideband noise (\( T_{ThN} \)) among AVCN marginal shell (a and c) and central core units (b and d). Threshold was defined as stimulus level in dB SPL required to produce a driven rate of 10 spikes/s. e and f: distributions of \( T_{ThN} - T_{ThT} \) for the marginal shell and central core populations, respectively.
results in Fig. 5 illustrate that an AVCN shell unit can exhibit a wide dynamic range, 64 dB, even though the maximum driven rate was low, 27 spikes/s. If the activities of such a unit contribute significantly to encoding stimulus intensity, then their low discharge rates imply that the strengths of synapses formed between the neuron’s axons and their target neurons would have to be greater than usual. The results in Fig. 5, c and f, illustrate that rate-level function of a shell unit can include inhibitory (i.e., negative values of driven rate) and excitatory responses at different stimulus levels.

Three typical AVCN core units are represented in Fig. 6, illustrating their normalized rate-level functions for tones and noise. Physiological properties (CF, SR, etc.) of each core unit presented in this and other figures are listed in Table 2. These core units exhibited low thresholds to both tones and noise, rose quickly to their maximum driven rates, were saturated at higher stimulus levels, and exhibited narrow dynamic ranges, 34–49 dB.

**Dynamic ranges**

Distributions of dynamic ranges to tones and noise among the AVCN shell and core populations are shown in Fig. 7. In the shell population, the weakly/not-driven units were excluded here because their dynamic ranges could not be well determined. The shell units exhibited a wide distribution of dynamic ranges, 20–90 dB to tones (Fig. 7a) and 10–80 dB to noise (Fig. 7c). In Fig. 7, a and c, about half of the well-driven shell units exhibited wide dynamic ranges >50 dB. Put another way, a large majority (68%) of the well-driven shell units exhibited dynamic ranges >50 dB to tones, noise, or both. In contrast, the core units exhibited a narrow unimodal distribution of dynamic range with a mode at 35 dB both to tones (Fig. 7b) and noise (Fig. 7d). Only 9 and 12% of the core units exhibited dynamic ranges >50 dB to tones and noise, respectively. On the basis of reports in the literature (e.g., Godfrey et al. 1975; Rhode and Smith 1986; Winter...
TABLE 2. Physiological properties of AVCN central core units

<table>
<thead>
<tr>
<th>Unit</th>
<th>CF (kHz)</th>
<th>SR, spike/s</th>
<th>PSTH</th>
<th>EIA</th>
<th>$M_T$, spike/s</th>
<th>$M_N$, spike/s</th>
<th>$T_h$, dB</th>
<th>$T_{th}$, dB</th>
<th>$DR_T$, dB</th>
<th>$DR_N$, dB</th>
<th>Latency, ms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q65-25</td>
<td>6.90</td>
<td>65</td>
<td>PL</td>
<td>III</td>
<td>203</td>
<td>149</td>
<td>1</td>
<td>17</td>
<td>49</td>
<td>42</td>
<td>3.6</td>
</tr>
<tr>
<td>Q51-04</td>
<td>7.80</td>
<td>65</td>
<td>ch-S</td>
<td>III</td>
<td>286</td>
<td>141</td>
<td>-18</td>
<td>8</td>
<td>50</td>
<td>45</td>
<td>3.1</td>
</tr>
<tr>
<td>S11-13</td>
<td>6.90</td>
<td>0.0</td>
<td>ch-S</td>
<td>I/III</td>
<td>260</td>
<td>250</td>
<td>2</td>
<td>16</td>
<td>28</td>
<td>34</td>
<td>3.5</td>
</tr>
<tr>
<td>S11-03</td>
<td>10.4</td>
<td>50</td>
<td>ch-O</td>
<td>III</td>
<td>300</td>
<td>NA</td>
<td>-10</td>
<td>20</td>
<td>35</td>
<td>NA</td>
<td>3.2</td>
</tr>
<tr>
<td>S11-04</td>
<td>10.4</td>
<td>12</td>
<td>ch-S</td>
<td>III</td>
<td>350</td>
<td>253</td>
<td>-12</td>
<td>5</td>
<td>21</td>
<td>36</td>
<td>2.9</td>
</tr>
</tbody>
</table>

Units are arranged in the order of their appearance in the text. NA, not available; ch-S, sustained chopper; ch-O, other chopper. For other abbreviations, see Table 1.

and Palmer (1995), one may expect to see some onset-type core units exhibit wide dynamic ranges. The present sample of AVCN core units included only a small number of units with dynamic ranges >50 dB. The reason for a seeming discrepancy is not clear. Fisher’s exact test indicated that the differences between the AVCN shell and core populations were significant regarding dynamic ranges to tones ($P < 0.001$) and to noise ($P = 0.003$).

Frequency response areas

Figures 8–10 show frequency response areas of AVCN shell units, and Fig. 11 shows those of typical AVCN core units. Figure 8 represents four strongly driven shell units that exhibited monotonic rate-level functions. In each panel, the horizontal dotted line represents zero driven rate. A distinctive feature of the units represented in Fig. 8, $a$–$c$, was that they exhibited narrow, sharply tuned response areas over a wide range of tone levels including 80 or 90 dB SPL. In Fig. 8, $a$ and $b$, there were some recognizable inhibitory areas, i.e., areas with negative driven rate values (denoted by asterisks), surrounding the excitatory area. In the unit of Fig. 8$c$, although the response area at 80 dB SPL was somewhat broader than those of Fig. 8, $a$ and $b$, it still retained a distinct peak and was narrower than those of typical AVCN core units (shown below). The unit in Fig. 8$d$ is unusual because it exhibited a high threshold (56 dB SPL) and two clearly separated excitatory areas along the frequency axis. Both regions of frequency remained restricted even at 80 dB SPL, and the unit did not exhibit saturation at any of the frequency regions.

The units in Fig. 8, $a$–$c$, exhibited wide dynamic ranges. The dynamic ranges to tones and noise for unit S3-07 were 89 and 74 dB (Fig. 2). The corresponding values for unit S03-09 were 66 and 50 dB, and those for unit S04-17 were 85 and 62 dB (Table 1).

Figure 9 shows frequency response areas of two strongly driven shell units that exhibited nonmonotonic rate-level functions to pure tones at CF. The unit in Fig. 9$a$, whose rate-level function was reported in Ghoshal and Kim (1996b), became increasingly wider, extending to lower frequencies far below the CF at 90 dB SPL. The best frequency (i.e., the stimulus frequency corresponding to the peak of the response area) was shifted to lower frequencies with increasing level above 50 dB SPL. In contrast, the unit in Fig. 9$b$ exhibited a sharply tuned frequency response area even at 90 dB SPL. The driven rate at the peak of this unit’s response area (at 15.6 kHz) decreased at 70 and 90 dB SPL compared with that at 50 dB SPL, consistent with the unit’s rate-level function shown in Fig. 5$a$.

Figure 10 shows response areas of three moderately driven shell units. The rate-level functions of two of these units, namely Q65-27 and S11-11, are shown in Fig. 5. Unit Q65-27 (Fig. 10$a$) exhibited a narrowly tuned response even at 70 dB SPL and exhibited a low driven rate (~20 spikes/s) at its CF at 70 dB SPL. Unit S11-11 (Fig. 10$b$) exhibited complex frequency response areas with multiple regions of excitatory and inhibitory areas located at different frequency regions at different stimulus levels. At 30 dB SPL, however, this unit exhibited a recognizable excitatory peak at 6.25 kHz. Unit S02-1 (Fig. 10$c$) exhibited a markedly nonmonotonic rate-level function. At 10 dB SPL, the response area had a well-defined excitatory peak (corresponding to the CF) and neighboring inhibitory areas. At ≥30 dB SPL, the excitation became inconspicuous and the inhibition became the dominant polarity of the response. The inhibitory areas were large at 50 dB SPL but became smaller at 60 dB SPL. The EIA type and the rate-level functions of this unit are provided below.

![Fig. 7](http://jn.physiology.org/)

**FIG. 7.** Distributions of dynamic ranges to pure tones at CF ($a$ and $b$) and to wideband noise ($c$ and $d$) for AVCN marginal shell units ($a$ and $c$) and AVCN central core units ($b$ and $d$).
Response areas of four typical AVCN core units are shown in Fig. 11. At low levels, all units exhibited well-defined excitatory peaks. With increasing level, the responses became larger, broader (particularly extending toward lower frequencies), and saturated. Often, there were inhibitory areas (denoted by asterisks) in these units' response areas, as seen in Fig. 11, a, b, and d. At ~90 dB SPL, the units exhibited a saturated excitatory response to nearly all frequencies below the CF. This relatively simple and typical behavior of the AVCN core units is similar to that of AN fibers (e.g., Rose et al. 1971).

Comparing the response areas of AVCN shell and core units (Figs. 8–11), we note that they are different as follows: 1) at high levels, the core units' responses tended to be saturated over a broad range of frequencies whereas the shell units' responses tended to maintain more visible peaks; 2) the core units' response level relationships tended to be monotonic, whereas those of the shell units were often strongly nonmonotonic; and 3) there was a greater tendency among the shell units to exhibit inhibitory areas of larger magnitude and wider frequency extent than among the core units (Figs. 5, 6, and 8–11, plus data not shown).
PSTH types

The PSTH patterns of eight shell units are shown in Fig. 12. The PSTHs were classified into various types according to the schemes of Pfeiffer (1966), Godfrey et al. (1975), and Rhode and Smith (1986). Units in Fig. 12, a and b, exhibit pause-build patterns. The pause-build-type PSTHs have been commonly observed among neurons of the dorsal CN (DCN) (e.g., Godfrey et al. 1975) and have not been previously reported among AVCN neurons. Figure 12, c–e, shows different types of onset patterns exhibited by AVCN shell units. Nearly one-third of the AVCN shell units exhibited PSTHs that did not fit into any of the existing standard PSTH types; thus we called them unusual. Regularity analysis (data not shown) with the use of the coefficient of variation (CV), i.e., the mean of the interspike interval divided by the SD, was of limited use in classifying these unusual units. All of these unusual units exhibited irregular discharge patterns with mean CVs usually >0.6. Some of the unusual PSTH patterns of the shell units are shown in Fig. 12, f–h. The PSTH patterns of AVCN core units are shown in Fig. 13: primary-like type (a) (Pfeiffer 1966); sustained chopper type (b) (e.g., Young et al. 1988); and “other” chopper type (c) (Parham and Kim 1992).

The distributions of the PSTH types of the AVCN shell and core units are shown in Fig. 14. The PSTH type distribution for the shell units included only the well-driven units because the weakly/not-driven shell units exhibited few spikes in response to the stimulus and their PSTH types could not be readily defined. The well-driven shell units mostly exhibited unusual, pause-build, and onset PSTH types. Few among them were primary-like or chopper types. In contrast, the core units exhibited mostly primary-like and chopper PSTH types, with some onset and unusual types and no pause-build type. The prevalence of primary-like and chopper PSTH types among the AVCN core units is consistent with the AVCN literature (e.g., Shofner and Young 1985). The Fisher’s exact test regarding the distribution of PSTH types yielded a highly significant difference between the two neural populations (P ≪ 0.001).

Latencies

The latencies of response to tone burst at CF were examined for the AVCN shell and core units. Their distributions are shown in Fig. 15. The shell units exhibited a wide distribution of latencies ranging from 2.4 ms to values >10 ms. The distribution for most of the shell units was centered around 3.75 ms. Several shell units, however, exhibited a shorter latency of 2.4 ms. The core units’ distribution was more homogeneous and nearly unimodal with a mode at 2.75 ms. The Fisher’s exact test determined that the difference between the latency distributions of the two neural populations was significant (P = 0.023).

EIA types

The EIA types were examined among the AVCN shell and core populations. EIA types II and IV have been typically observed among DCN neurons (e.g., Young 1984) and have not been previously reported among AVCN neurons. The present study found that EIA types II and IV were included...
in the AVCN shell population. The unit represented in Fig. 16, a and b, exhibited a strong, monotonic rate-level function to pure tones at CF (Fig. 16a), and yet was little driven by wideband noise (Fig. 16b). This unit's SR was zero. Thus properties of this unit resemble those of EIA type II. [Note: a difference between this unit and a typical EIA type II unit is that the rate-level function of the latter to tones is saturated with a slight decline at high stimulus levels (e.g., Young 1984), whereas that of the former (Fig. 16a) did not exhibit a saturation or decline at high levels.] Figure 16, c–f, shows examples of EIA type IV behavior among AVCN shell units. The unit in Fig. 16, c and d, exhibited an excitatory response to the CF tones at 10–30 dB SPL and inhibitory response to the CF tones at higher levels. The complete frequency response of this unit is shown in Fig. 10c. Regarding response to noise, this unit exhibited strong inhibition at levels between ~20 and 60 dB SPL and weak excitation at higher levels (Fig. 16d). This unit corresponds to EIA type IV. The unit in Fig. 16, e and f, also exhibited a nonmonotonic rate-level function that rose to strong excitation at low levels and declined to near zero at 60 dB SPL, rising again with a further increase in stimulus level. This unit exhibited little or no response to noise. This unit corresponds to EIA type IV-T, a subclass of type IV (Shofner and Young 1985).

Distributions of the EIA types of the shell and core units are shown in Fig. 17. Although the core units exhibited mainly types III followed by type I/III, the shell units exhibited mainly types I/III followed by type III. A noteworthy contrast between the two populations was the presence of types IV and II in the shell population and the complete absence of type II units and only one type IV unit in the core population. There were some units in both the AVCN shell and core that could not be classified into any of the known EIA types and thus were collectively grouped as unusual. For example, in a moderately driven shell unit, S11-11, represented in Figs. 5, e and f, and 10b, the SR was 27 spikes/s and there was a weak excitatory response to CF tones, a prominent inhibitory response to high-level noise, and a weak excitatory response to low-level noise. One might consider classifying this unit as EIA type III. However, this...
unit is different from an EIA type III unit in that the latter is typically excited by noise whereas the former is inhibited by high-level noise. The Fisher's exact test determined that the difference between the two populations regarding the EIA types was significant ($P = 0.011$).

Summary of Fisher's exact tests

Table 3 lists the outcomes of Fisher's exact tests for differences between the AVCN shell and core populations regarding all of the physiological characteristics examined.

Relationship between EIA and PSTH types

The relationships between the EIA types and the PSTH types of the AVCN shell and core units are indicated in Tables 4 and 5, respectively. CN units with low CF (below ~1.5 kHz) often exhibit discharges phase-locked to the sinusoidal signal of the CF tone. Consequently, the PSTHs of such units cannot be readily classified into the standard PSTH types (e.g., Pfeiffer 1966; Rhode et al. 1983), and therefore are designated as the “phase-locked” type. A striking difference between the shell and core populations noticeable in Tables 4 and 5 is that the EIA type I/III and III units among the marginal shell units were of mostly unusual and pause-build PSTH types, whereas those of the core units were mostly of primary-like and chopper PSTH types. There were two shell units with low CFs

![Fig. 12. PSTHs of 8 AVCN marginal shell units to pure tones at CF. on-C, onset-chopper; on-L, onset excitatory response followed by a low-level sustained excitatory response; on-inh, onset excitatory response followed by an inhibitory response.]

![Fig. 13. PSTHs of 3 typical AVCN central core units to pure tones at CF. chop-S, sustained chopper; chop-O, chopper “other” than chop-S and chop-T, transient chopper.]

![Fig. 14. Distribution of PSTH types of the AVCN marginal shell units (a) and the AVCN central core units (b). PL, primary-like; chop, chopper; on, onset; PB, pause-build; unus., unusual.]

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in support of the stated hypothesis, the AVCN marginal shell is significantly different from the AVCN core regarding all of the many single-unit physiological characteristics examined, i.e., maximum driven rate, threshold, rate-level function, dynamic range (with each of the above measured with both pure tones and noise), PSTH type, latency to pure tones, and EIA type. Previously reported data (Ghoshal and Kim 1996b) revealed that the two neural populations were also significantly different regarding SR.

**Rate-level functions and dynamic ranges**

A most prominent characteristic of the well-driven AVCN marginal shell units was the prevalence of units exhibiting rate-level functions with wide dynamic ranges. A large majority (68%) of this category of AVCN shell units exhibited dynamic ranges >50 dB to tones or noise. Many of the shell

**TABLE 3. Outcomes of Fisher's exact test for differences between the AVCN marginal shell and central core populations regarding various physiological characteristics**

<table>
<thead>
<tr>
<th>Physiological Characteristics</th>
<th>p Value From Fisher's Exact Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum driven rate to tone, $M_T$</td>
<td>&lt;=0.001</td>
</tr>
<tr>
<td>Maximum driven rate to noise, $M_N$</td>
<td>&lt;=0.001</td>
</tr>
<tr>
<td>$M_T / M_N$</td>
<td>0.0045</td>
</tr>
<tr>
<td>$T_h$</td>
<td>&lt;=0.001</td>
</tr>
<tr>
<td>$T_{th}$</td>
<td>&lt;=0.001</td>
</tr>
<tr>
<td>$TH_T - TH_T$</td>
<td>0.038</td>
</tr>
<tr>
<td>$DR_T$</td>
<td>&lt;=0.001</td>
</tr>
<tr>
<td>$DR_N$</td>
<td>0.003</td>
</tr>
<tr>
<td>PSTH type</td>
<td>&lt;=0.001</td>
</tr>
<tr>
<td>Latency</td>
<td>0.023</td>
</tr>
<tr>
<td>EIA type</td>
<td>0.011</td>
</tr>
</tbody>
</table>

For abbreviations, see Table 1.
units exhibited monotonically rising rate-level functions with little or no saturation even at high levels of ≳ 90 dB SPL (Fig. 2; Table 1). Few of these units exhibited complete saturation at high levels.

Some AN fibers with low SRs have been observed to exhibit wide dynamic ranges and high thresholds (e.g., Evans and Palmer 1980; Liberman 1978; Winter et al. 1990). One major difference between the present observation and those of the AN fibers in this regard is that wide-dynamic-range units are a large majority among the acoustically well-driven AVCN shell units, whereas their AN counterparts are a small minority among AN fibers. In addition, many of the AVCN shell units with monotonically rising rate-level functions had low thresholds, whereas their AN counterparts tend to have higher thresholds (Winter et al. 1990). The reason for the latter difference is not clear. Possible explanations for this difference are that a descending excitatory input from MOC collaterals and/or an ascending input from type II AN fibers conveying a signal from outer hair cells (OHCs) to a shell unit may make the threshold of a shell unit lower than that of a low-SR AN fiber.

As stated in the INTRODUCTION, we make the interpretation that an excitatory input to a shell unit from MOC collaterals is key to the shell unit’s wide dynamic range (Brown et al. 1988b; Kim et al. 1995, their Fig. 1). An input from MOC collaterals to a shell unit would counteract an amplitude compression of the cochlear amplifier output at high levels. An amplitude compression would arise as an effect of a negative feedback of MOC input to the cochlear amplifier. Without an MOC collateral input, an AN fiber or an AVCN unit would exhibit a compression of the output amplitude, and consequently a narrow dynamic range. With MOC collateral input, an AVCN shell unit would exhibit a wider dynamic range and a more accurate representation of the absolute stimulus intensity than either an AN fiber or a typical AVCN core unit.

An alternative mechanism proposed for generation of a wide dynamic range to pure tones is convergence of AN fibers of various CFs onto a target CN neuron (Rhode 1991). It is interesting that some of the AVCN shell units exhibited staircaselike rate-level functions (Fig. 2c; Ghoshal and Kim 1996b, their Fig. 2) resembling a schematic rate-level function predicted by Rhode (1991, their Fig. 12C) on the basis of the above hypothesis. One limitation of this mechanism is that it cannot help account for a wide dynamic range to wideband noise because AN fibers at various CFs would all be saturated regardless of their CFs under wideband noise stimulation. In contrast, the mechanism of excitation via MOC collaterals discussed above would be effective for both pure tones and wideband noise.

At the level of the CN, the only other units known to have wide dynamic ranges are a subset of onset-type units (e.g., Godfrey et al. 1975, their Fig. 6; Rhode and Smith 1986, their Fig. 8; Winter and Palmer 1995, their Fig. 12). Some, but not all, of the onset units with wide dynamic ranges are the onset-chopper type often found in the posteroventral cochlear nucleus (PVCN) (Rhode and Smith 1986; Rhode et al. 1983). The PVCN onset-chopper units, which correspond to large, multipolar cells, are principally located in the multipolar cell region in an anterior part of the PVCN (Smith and Rhode 1989). Among the present sample of well-driven shell units, nearly a quarter were onset-type units. Two were onset-chopper type units, both of which exhibited wide dynamic ranges, >80 dB to pure tones and >60 dB to noise. Whether any functional or anatomic relationship exists between these shell onset-chopper units (or shell units in general) observed in the present study and the PVCN onset-chopper units observed by Rhode and Smith remains to be investigated. Interestingly, both the AVCN marginal shell (Kim et al. 1995) and the PVCN (Thompson and Thompson 1991) have been reported to project to the perioliary area, including projections to the MOC neurons.

### Frequency response areas

Regarding frequency response areas, which may also be called rate-frequency functions, one of the interesting features was that they had narrowly tuned peaks even at high stimulus levels such as 80 or 90 dB SPL, in some AVCN shell units (Figs. 8, a–c, and 9b). These were quite distinct from typically broad, saturated responses of AVCN core units (Fig. 11). The units of Fig. 8, a–c, exhibited wide dynamic ranges to pure tones, 66–89 dB (Fig. 2c; Table 1), although the unit of Fig. 9b exhibited a nonmonotonic rate-level function with a narrow dynamic range (Fig. 5a).

A possible mechanism that may underlie a distinct narrow peak in a rate-frequency function at a high stimulus level and a wide dynamic range is as follows. An excitatory input from MOC collaterals to a shell unit is expected to produce not only wide dynamic ranges in rate-level functions as discussed above but also a distinct peak in a rate-frequency function at a high stimulus level. For this discussion, we postulate that a shell unit exhibiting such behavior receives excitatory inputs from AN fibers and MOC collaterals with common CFs all within a restricted range. In such a case, an excitatory MOC collateral input to a shell unit should help produce monotonic unsaturated

**TABLE 4. Relationship between PSTH types (rows) and EIA types (columns) for the AVCN marginal shell units**

<table>
<thead>
<tr>
<th></th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
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<th>Total</th>
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<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Ph-L</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td></td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Chopper</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Onset</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>PB</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unusual</td>
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<td>1</td>
<td>1</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
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<td>5</td>
<td>2</td>
<td>3</td>
<td>22</td>
<td>23</td>
</tr>
</tbody>
</table>

For abbreviations, see Table 1.

**TABLE 5. Relationship between PSTH types (rows) and EIA types (columns) for the AVCN central core units**

<table>
<thead>
<tr>
<th></th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>Unusual</th>
<th>Total</th>
</tr>
</thead>
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<td>13</td>
<td>1</td>
<td>26</td>
<td></td>
</tr>
<tr>
<td>Ph-L</td>
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<td>3</td>
<td>3</td>
<td></td>
<td>6</td>
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</tr>
<tr>
<td>Chopper</td>
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<td>9</td>
<td>1</td>
<td>16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Onset</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PB</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Unusual</td>
<td>1</td>
<td>4</td>
<td>0</td>
<td>2</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>3</td>
<td>20</td>
<td>32</td>
<td>0</td>
<td>4</td>
<td>60</td>
</tr>
</tbody>
</table>

For abbreviations, see Table 1.
rate-level functions of a shell unit for pure-tone frequencies not only at the CF but also around the CF because, for all frequencies around the CF, the effect of amplitude compression taking place in the cochlear amplifier should be minimized in the response of a shell unit by the presence of a MOC collateral input. If rate-level functions for various frequencies around the CF are all unsaturated over a wide range of stimulus levels, a consequence is that a rate-frequency function should exhibit a narrow distinct peak for various stimulus levels, including high levels.

Another interesting feature of the AVCN shell units was that the effectiveness of wideband noise relative to pure tones was greater among AVCN shell units than among AVCN core units. For example, difference in threshold to noise and to tones, $T_{th} - T_{th}$, tended to be lower among shell units (mode at 5 dB, Fig. 4e) than among core units (mode at 15 dB, Fig. 4f). Also, the ratio of the maximum driven rates to wideband noise and pure tones, $M_{max}/M_{T}$, was greater than unity in ~45% of the well-driven AVCN shell units (Fig. 3e), whereas it was less than unity for most of the AVCN core units (Fig. 3f). These data indicate that pure tones were more effective than wideband noise for most of the core units (Fig. 4f). Winter and Palmer (1995) and Palmer et al. (1996) found that a subset of onset-type units of the VCN core exhibited behavior analogous to that of AVCN shell units, i.e., higher $M_{max}$ than $M_{T}$ and lower $T_{th} - T_{th}$ among onset units than among VCN chopper units or AN fibers. Those researchers interpreted this to mean that some onset units may receive excitatory inputs from an array of AN fibers having a wide range of CFs with each input being weighted according to the frequency and that the units consequently integrate signals over a wide bandwidth. Because the behavior of some AVCN shell units of the present study is similar to that of the onset units of Winter and Palmer (1995) and Palmer et al. (1996), a similar mechanism of integration over a wide bandwidth may also underlie some AVCN shell units. The difference found within the present study between the AVCN shell and core populations may imply that there exist more substantial wideband off-CF inputs to shell units than to core units.

It should be noted that, in shell units exhibiting wide dynamic ranges, e.g., units S03-07, S03-09, and S04-17, noise was not always more effective than pure tones. That is, $T_{th}$ was higher than $T_{th}$ by 5–25 dB, and, in some cases, $M_{max}$ was lower than $M_{T}$ (Table 1). Such shell units may not receive wideband off-CF inputs, and that may be partly related to the narrow rate-frequency functions at high stimulus levels in these units (Fig. 8, a–c), as discussed above. Therefore the mechanism of integration over wideband off-CF inputs (Rhode 1991; Winter and Palmer 1995) may not be applicable to such shell units.

**PSTH types**

Regarding the PSTH types, a surprising new finding was a considerable representation of the pause-build PSTH type among AVCN shell units (Fig. 12, a and b), which comprised nearly 30% of the well-driven AVCN shell units (Fig. 14). Pause-build units of the AVCN shell appear to exhibit somewhat lower $M_{T}$s at CF than the pause-build units of the DCN (Parham and Kim 1992). Regularity analysis could be performed for only a subset of the AVCN shell pause-build units because of their low discharge rate. However, those AVCN shell units for which such analysis was possible did reveal low CVs, with mean CVs between 0.35 and 0.4. This was consistent with the observation of DCN pause-build units (Parham and Kim 1992). Although we looked for a possible correlation among the AVCN shell units between the PSTH type and other response characteristics, e.g., dynamic range or frequency response area, it was difficult to find any clearly recognizable correlation.

**EIA types**

A surprising new finding of the present study is that EIA type II units were encountered in the AVCN shell. To our knowledge, no type II units were previously reported in the VCN. Because EIA type II behavior is postulated to arise from inhibitory inputs (Arle and Kim 1991; Young and Voigt 1982), the presence of such units may be interpreted as a substantial presence of inhibitory inputs in the AVCN shell. Presence of type IV units also implies inhibitory inputs (Nelken and Young 1994; Voigt and Young 1980). These interpretations, together with the observations of prominent inhibitory response areas (Fig. 10), further suggest that the AVCN shell has more substantial inhibitory inputs than the AVCN core.

The correlation between the PSTH types and the EIA types of the marginal shell units was not the same as the previous observations of the VCN and DCN. The type I/III and III units were reported to show primarily the chopper PSTH type in the VCN and DCN (Shofner and Young 1985). In the present sample of the AVCN shell units, however, the chopper PSTH type was rare among type I/III and III units (Table 4). The present AVCN shell sample included EIA type IV. Shofner and Young (1985) reported some type IV units in the caudal AVCN. Because those researchers did not localize the units in the AVCN, however, it is not clear whether their sample of type IV AVCN units corresponds to ours.

**Possible functions mediated by shell units**

Wide dynamic ranges exhibited by AVCN shell units suggest that they may be better suited to the encoding of intensity over a wide range than AVCN core units exhibiting narrower dynamic ranges. The AVCN shell projects to the superior olivary complex, including projections to MOC neurons (Kim et al. 1995). Considering that MOC neurons would need accurate information about absolute stimulus intensity to provide a proper negative feedback control signal to the cochlear amplifier, the physiological and anatomic observations from the AVCN shell support a hypothesis that the AVCN shell forms an important link in the OHC-MOC reflex circuit.

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