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Laser Doppler measurements of cochlear blood flow during loud sound exposure in the guinea pig

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This investigation examined the effects of loud sound of different frequencies and intensities on cochlear blood flow as measured by the laser Doppler flowmeter. Cochlear blood flow was measured in anesthetized guinea pigs during a 1 h exposure to either a 2, 4, or 12 kHz pure tone or high-pass noise (10–40 kHz) at 90, 103, or 110 dB SPL. Cochlear function was assessed using the compound action potential audiogram before and after exposure. There was no change in blood flow in the second turn with a 2, 4, or 12 kHz tone but there was a significant ($P < 0.05$) decline in flow in the first cochlear turn at the end of either the 12 kHz tone or high-pass noise exposure at 103 and 110 dB SPL. There were elevations in the thresholds of the cochlear compound action potential after all but the 90 dB exposures to 12 kHz or high-pass noise. No such changes were observed in blood flow or electrophysiology in control animals. These findings demonstrate that there is a small but significant decline in cochlear blood flow with high intensity sound exposure. However, the relationship between this change in blood flow and the development of cochlear damage is unclear.

Laser Doppler flowmeter; Cochlear blood flow; Acoustic trauma; Compound action potential; Guinea pig

Introduction

Loud sound can result in structural changes to the cochlea, particularly to the hair cells, supporting cells, and neural elements in the organ of Corti. Although there is now considerable evidence of the morphological changes and the relationship to the characteristics of the sound exposure and the functional deficit that develops, the mechanisms by which this damage occurs have not yet been established.

An impairment of cochlear blood flow, presumably resulting in hypoxia and a reduction of essential metabolites during a period of higher metabolic demand has been suggested as one mechanism by which noise may cause damage in the cochlea (Misrahy et al., 1958; Hawkins, 1971). However, a study of the literature reveals that the evidence of changes in cochlear blood flow and the possible role of these alterations in the pathogenesis of noise-induced cochlear damage are unclear. Much of the basis for a vascular hypothesis comes from indirect measurements of cochlear blood flow, such as histological changes in cochlear vasculature and alterations in cochlear oxygen tension. Histological changes in the cochlear vasculature, such as swelling of endothelial cells and constriction of capillaries, were described by Hawkins (1971) after prolonged noise exposure. A number of subsequent studies have demonstrated similar changes, but have also provided quantitative evidence of small, but significant alterations in the orientation, frequency and spacing of red cells, capillary constriction and endothelial cell swelling in various vascular beds in the cochleae of noise-exposed animals (Vertes et al., 1979; 1982; Axelsson et al., 1981; Dengerink et al., 1985; Shaddock et al., 1985; Smith et al., 1985). Such changes in the vasculature have been interpreted as reflecting a decrease in blood flow during noise exposure. A dramatic decrease in oxygen tension of the cochlear fluids has been demonstrated during noise (Misrahy et al., 1958; Maass et al., 1976, 1978) which may possibly reflect a decrease in

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blood flow. However, contrasting with these reports is an investigation by Nuttall et al. (1981) in which no changes were found in the oxygen tension of scala tympani following a variety of loud sound exposures up to 8 min in duration. These authors demonstrated that some of the dramatic changes seen in previous studies (Misrahy et al., 1958; Maass et al., 1978) could be due to an effect on the oxygen electrode by cooling of the cochlea due to the method of sound exposure.

There are surprisingly few direct measurements of alterations in cochlear blood flow during noise exposure. Perlman and Kimura (1962) measured the velocity of red cells in the vessels of the lateral wall of the cochlea and found no change at low intensities but an increase in velocity with sound pressure levels up to about 130 dB SPL above which there was a decrease in the velocity. The observation of a decrease in the rate of hydrogen clearance from the cochlea after 115 dB wide-band noise by Maass et al. (1978) was evidence of a decrease in blood flow. Prazma et al. (1983) demonstrated, with the microsphere technique, a substantial increase in blood flow, but in the basal turn only, during a wide-band noise exposure (113 dB, 13 min). However, Hultcrantz, using the microsphere technique, found no evidence of altered flow in the anesthetized cat (Hultcrantz et al., 1979) or unanesthetized rabbit (Hultcrantz, 1979) during a white-noise exposure (100–120 dB, 6 min).

Thus, the literature shows no consistent evidence on the occurrence or direction of alterations to cochlear blood flow as a result of loud sound exposure. One major problem has been the variety of methods used to assess blood flow in the cochlea. Although histological techniques provide information on morphological alterations in the vasculature, there is the question of how to interpret these results with respect to changes in blood flow. The microsphere method, while offering a quantitative measure, requires large numbers of microspheres in the tissue for statistical purposes. This can be difficult to achieve in the cochlea where the total blood flow is small. Unfortunately, estimation of dynamic changes in cochlear blood flow are limited in the microsphere technique which permits only a few measurements on an individual subject. Measurement of oxygen tension is an indirect indicator of blood flow as its also reflects alterations in oxygen utilization.

Direct measurement of dynamic alterations in blood flow in the cochlea during different noise exposures is needed in order to establish clearly whether alterations in cochlear blood flow do occur and have any relationship to the development of noise-induced damage. Recently, the laser Doppler flowmeter has been used as a method of studying cochlear blood flow (Miller et al., 1983; Goodwin et al., 1984) and the qualitative alterations observed during various drug and experimental manipulations indicate that this may be a useful method for studying the question of the effects of noise on cochlear blood flow. The present study was undertaken to investigate the qualitative changes in cochlear blood flow through the cochlea, using the laser Doppler technique, during different types of sound exposure.

Materials and Methods

Guinea pigs of either sex weighing between 250 and 400 g were used in this study. Each animal was anesthetized with diazepam (5 mg/kg) and fetanyl (0.32 mg/kg) and given supplemental doses of anesthetic every 1/2 (fentanyl) or 2 (diazepam) h. The animals were tracheotomized, then wrapped in a heating blanket and placed on an operating table with the head held rigidly in a head holder. Rectal temperature was maintained at $38 \pm 1°C$ throughout the experiment. The left auditory bulla was opened using a ventral approach to expose the cochlea but the ossicles and tympanic membrane were left intact. All animals were free of any middle ear disease as determined by inspection with the operating microscope. The periosteum overlying the cochlea was removed carefully using cotton pledgets and a 40 gauge insulated silver wire was placed on the round window to record gross cochlear potentials with reference to a silver/silver chloride electrode placed in the neck muscles. Arterial blood pressure was recorded from a catheter inserted into the left carotid artery and connected to a blood pressure transducer. All experiments were carried out in a sound-attentuating and electrically shielded booth.

The needle probe (1.75 mm diameter) of a laser Doppler capillary perfusion monitor (model LD5000, MedPacific Corp., Seattle, WA, USA) was placed on the bone overlying the spiral ligament of the first or second turns. The flow output of the laser Doppler flowmeter was recorded on a chart recorder along with continuous measurement of arterial blood pressure. The 'DC' value output of the device (a measure of tissue reflectance) was monitored periodically throughout the experiment.

Cochlear function was monitored using the gross cochlear potentials recorded from the round window electrode. The compound action potential (CAP) in response to tone bursts (2–35 kHz, 1 ms rise time, 15 ms duration) was amplified 10 ×, low pass filtered (cut off frequency, 5 kHz; model P16 amplifier, Grass Instruments, MA, USA) and displayed on an oscilloscope. Tones were delivered to the ear by a 1/2 inch condenser microphone sound source inserted into a speculum placed in the outer ear canal. The sound delivery system was calibrated using a probe tube microphone inserted to within 1 mm of the tympanic membrane. The sound pressure level required to produce a just detectable response of the N_1 wave of the CAP (approx. 10 μV peak) was determined over the entire frequency range to produce an N_1 audiogram for each animal. Only animals with a normal N_1 audiogram, based on experience in this laboratory (Brown et al., 1983), were included in this study.

Animals were exposed to either a 2, 4 or 12 kHz pure tone or high-pass noise (10–40 kHz) at an intensity of 90, 103, or 110 dB SPL. The specific combination of exposure frequency and intensity is shown in Table I. The pure tones were delivered through the microphone sound source inserted into the speculum while the high-pass noise was presented free-field from a speaker (model 40-1375, Radio Shack Corp., Ft. Worth, TX, USA) placed 30 mm from the ear canal. The sound pressure level during free-field exposures was measured with an 1/8 inch condenser microphone placed approximately 10 mm from the entrance to the outer ear canal and attached to a sound level meter (model 2203, Brüel and Kjaer, Njaerum, Denmark) with a linear weighting. The spectral shape of the noise is shown in Fig. 1.

TABLE I

EXPERIMENTAL GROUPS

Laser Doppler probe position	Exposure frequency (kHz)	Exposure intensity (dB SPL)	*N*
1st turn	12	90, 103, 110 [a]	14
1st turn	high-pass noise (10–40 kHz)	90, 103, 110 [b]	13
2nd turn	2	110 [a]	3
2nd turn	4	90, 103, 110 [a]	14
2nd turn	12	110 [a]	4
1st turn	unexposed controls		4
2nd turn	unexposed controls		2

[a] Presented closed field.SPL as measured 1 mm from the tympanic membrane.

[b] Presented free field.SPL as measured at the entrance to the ear canal.

Experimental procedures

Baseline cochlear blood flow and blood pressure measurements were made over a 10–15 min period during which cochlear potentials were also recorded. The animals were then exposed to sound at intensities of 90, 103 or 110 dB SPL for a total of one hour duration. The location of the laser Doppler probe was varied according to the particular type of exposure that was used (Table I). The exposure was divided into six 10-min periods and the sound was turned off for 1 min at the end of each period in order to allow stable measures of cochlear blood flow. This was necessary to avoid

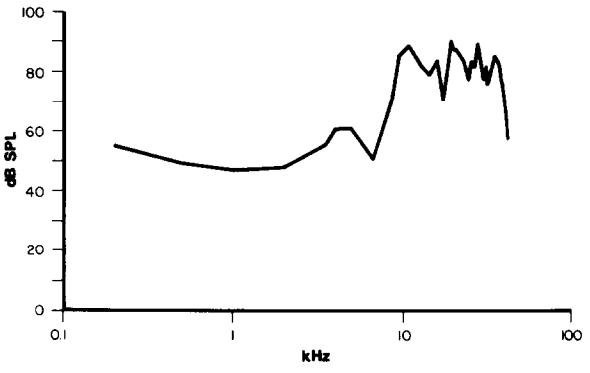

Fig. 1. Spectral analysis of the high-pass noise at 110 dB SPL measured at 10 mm from the entrance to the ear canal using an 1/8 inch microphone and Hewlett-Packard 640A wave analyzer with 100 Hz bandwidth.

the sound-induced artifact seen in the laser Doppler flow measurements (Thorne and Nuttall, in preparation). Cochlear potentials were recorded within 10 min following the last sound exposure and in some subjects flow and blood pressure measurements were continued for up to an hour in quiet. In those cases cochlear potentials were re-measured immediately following the 1 h quiet period. Six control animals were subjected to the same surgical procedures, but were exposed only to the ambient noise in the room. Cochlear blood flow in these animals was monitored over a 1 h 'simulated' exposure period.

In each animal an alteration in blood flow was determined as a proportion of the blood flow measured over the 10–15 min baseline period. Comparisons between exposed animals and controls were made using the Student's *t*-test. Means are expressed as ± 1 S.D. unless otherwise stated.

Results

Control animals

The mean CAP thresholds plotted against frequency (the compound action potential or N_1 audiogram) for control animals are shown in Fig. 2. The CAP audiogram shows a normal shape with a decline in thresholds for increasing frequency to about 20 kHz after which thresholds rise abruptly. There was no difference between thresholds at the beginning and end of simulated sound exposure.

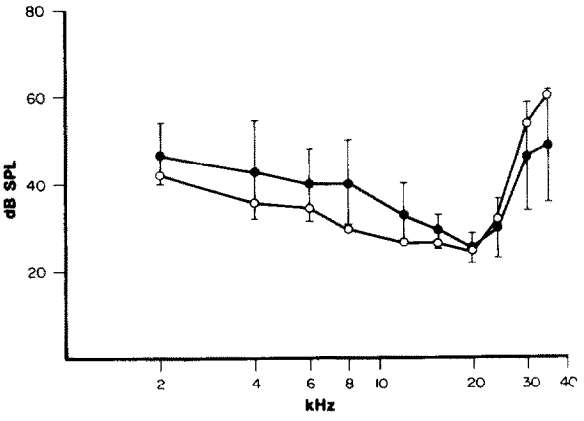

Fig. 2. The mean N_1 thresholds (dB SPL) at frequencies from 2 to 35 kHz for control animals (filled circles; $n = 6$) and experimental subjects prior to noise exposure (open circles; $n = 48$). Bars represent ± 1 S.D. from the mean for control animals.

Arterial blood pressure in control animals showed a slight decline during the simulated exposure from a mean of 54.0 (± 10.5) mmHg to 48.7 (± 11.0) mmHg (Fig. 3). Cochlear blood flow, at the end of the 1 h simulated exposure, ranged from 0.93 to 1.04 (mean: 0.98 ± 0.04; Table II) of the original flow.

Sound exposed animals

The mean pre-exposure CAP thresholds for all sound-exposed animals lay within normal limits as shown in Fig. 2. Mean alterations in CAP thresholds after the 1 h exposures at the various intensities and frequencies are shown in Fig. 4. Exposure to the 4 kHz pure tone at 90 dB SPL caused a small (5–15 dB), but significant ($P < 0.05$ at each test frequency) loss of CAP threshold (Fig. 4A), but there was no significant change in CAP threshold after either the 12 kHz (Fig. 4B) or high-pass noise exposure at 90 dB SPL (Fig. 4C). However, exposure to 4 kHz, 12 kHz, or high-pass noise at 103 and 110 dB SPL caused substantial losses in CAP threshold. The maximum threshold shift following the 4 kHz exposures occurred at 4–8 kHz (Fig. 4A) and the mean ($\pm$S.E.) loss averaged over these frequencies was 48.9 ± 4.12 dB after the 103 dB SPL exposure and 64 ± 1.76 dB after the 110 dB SPL exposure. There was a significant difference ($P < 0.05$) between the CAP loss after the 4 kHz exposure at 103 dB SPL and 110 dB SPL. Maximum threshold shifts following 12 kHz (Fig. 4B) and high-pass noise (Fig. 4C) occurred at 12–24 kHz. The mean ($\pm$S.E.) loss

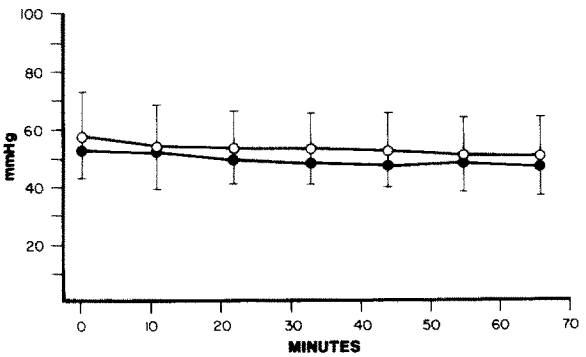

Fig. 3. Mean arterial blood pressure (mmHg) during the period of sound exposure for exposed animals (filled circles) or simulated exposure for controls (open circles).

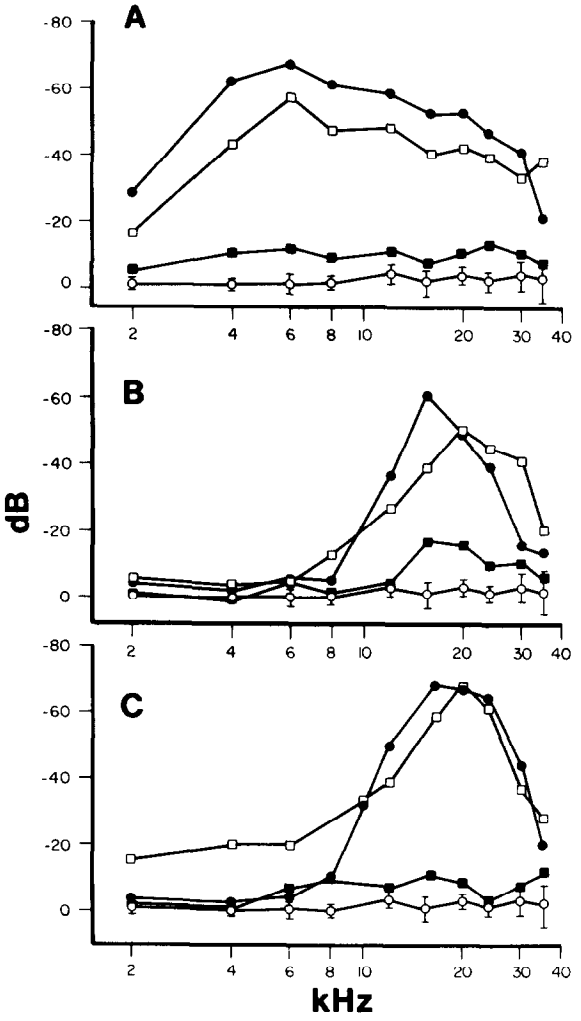

Fig. 4. Mean loss of N_1 thresholds (dB) at frequencies from 2 to 35 kHz for animals exposed to (A) 4 kHz, (B) 12 kHz and (C) high-pass noise at 90 (filled squares), 103 (open squares) or 110 dB SPL (filled circles). The threshold loss for control animals (open circles; mean ±1 S.D.) are also shown.

average over these frequencies for the 12 kHz exposures was 40.3 ± 4.9 dB after 103 dB SPL and 47.0 ± 5.6 dB after the 110 dB SPL exposures. Following the high-pass noise exposures, mean (± S.E.) maximum threshold shifts were 55.3 ± 5.7 dB after 103 dB SPL exposures and 62.2 ± 4.24 dB after 110 dB SPL exposures. The differences between either 12 kHz at 103 dB SPL and 110 dB SPL or high-pass noise exposures at the same intensities were not significant. The two animals exposed to the 2 kHz tone at 110 dB SPL showed an elevation of CAP threshold over all frequencies tested with a maximum of 64–78 dB at 2–4 kHz (data not shown).

The arterial blood pressure of sound-exposed animals showed little change during the course of the exposures. At the beginning of the exposure, blood pressure between animals ranged from 48 to 83 mmHg (mean 57.6 ± 14.7) and at the end of the exposure the pressures were 46–80 mmHg (mean 50.4 ± 13.6) (Fig. 3).

The results of the blood flow measurements are shown in Table II and Figs. 5 and 6. With the laser Doppler probe placed on the first turn, a significant ($P < 0.05$) decline in cochlear blood flow was measured during the 12 kHz pure tone or the high-pass noise exposure at either 103 or 110 dB SPL. There was no significant change in cochlear blood flow during a 12 kHz or high-pass noise exposure at 90 dB SPL. In contrast to the measurements in the first turn, there was no significant change in cochlear blood flow with any of the exposures with the laser Doppler probe placed on the second turn.

The time course of the changes in cochlear blood flow during a 12 kHz exposure is shown in

TABLE II

SUMMARY OF COCHLEAR BLOOD FLOW MEASUREMENTS

Laser Doppler probe position	Exposure frequency (kHz)	Exposure intensity (dB SPL)	Proportion of original cochlear blood flow after 1 h exposure
1st and 2nd turn	control		0.98 ±0.04 (6) [a]
1st turn	12	90	0.97 ±0.08 (4)
		103	0.85 [b] ±0.07 (4)
		110	0.69 [b] ±0.24 (5)
	high-pass noise (10–40 kHz)	90	0.90 ±0.17 (4)
		103	0.84 [b] ±0.12 (4)
		110	0.85 [b] ±0.13 (4)
2nd turn	2	110	1.03 ±0.06 (2)
	4	90	0.93 ±0.10 (4)
		103	0.96 ±0.06 (5)
		110	0.89 ±0.19 (4)
	12	110	0.96 ±0.10 (4)

[a] Sample size.

[b] $P < 0.05$ relative to control animals.

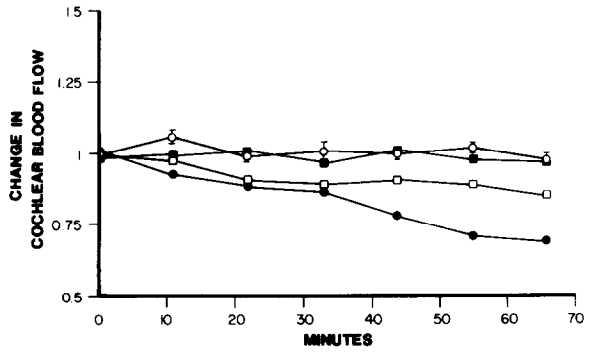

Fig. 5. The changes in cochlear blood flow (relative to the pre-exposure level) at different intervals (min) after the onset of a 12 kHz pure tone at 90 (filled squares), 103 (open squares) or 110 dB SPL (filled circles). The mean (open circles; ± S.D.) cochlear blood flow for control animals is also shown. Changes in cochlear blood flow during the 103 or 110 dB SPL exposures were significantly ($P < 0.05$) less than controls at all time intervals.

Fig. 5. Flow decreases began within 10–20 min of the onset of the 103 or 110 dB SPL exposure and showed either a continuing decline or plateau. The difference between the 103 and 110 dB SPL exposures was not significant. There was considerable variation in the extent of the decreases in cochlear blood flow among animals. For example, in the group exposed to 12 kHz at 110 dB SPL, decreases ranged from 7 to 71% by the end of the exposure (Fig. 6). There was no apparent relationship between the extent of decline in cochlear blood flow and either the magnitude of the reduction in arterial blood pressure (Fig. 6), or the size of the CAP threshold loss.

Blood flow showed no further significant changes in animals studied after the exposure. In other words there was no tendency for a continued decline of flow, nor of recovery, within a 30–60 minute period after the exposure. The threshold loss remained unaltered also, but blood pressure continued to decline following exposure.

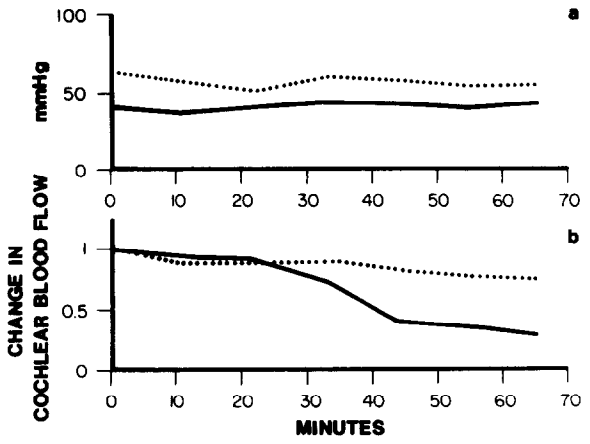

Fig. 6. A comparison of (a) arterial blood pressure and (b) cochlear blood flow for two animals (T-20, solid line; T-79, dotted line) exposed to a 12 kHz pure tone at 110 dB SPL. Blood pressure of both animals is unchanged during the exposure, but the decline in blood flow in T-20 is much greater than T-79.

Discussion

This study demonstrates clearly that cochlear blood flow in the anesthetized guinea pig may decrease by up to 70% in the first cochlear turn during high intensity (103 or 110 dB SPL), high frequency pure tone or high-pass noise exposure, but remains unchanged during lower intensity (90 dB SPL) sound exposure at these frequencies. In contrast, blood flow in the second turn was not altered during low or high frequency sound exposure at intensities from 90 to 110 dB SPL.

There are some methodological aspects of this study which need to be considered before discussing the implications of the results. The output of the laser Doppler instrument is proportional to the number and mean velocity of red cells moving within a given volume (Nilsson et al., 1980; Bonner and Nossal, 1981). It has been demonstrated that the output varies in a similar manner to other measures of blood flow such as microspheres, hydrogen clearance and electromagnetic flowmeters in other tissues (e.g. Kvietys et al., 1985). Although the laser Doppler measurements have not been compared with other measures of blood flow in the cochlea, a number of investigators (e.g. Miller et al., 1983; Goodwin et al., 1984; Dengerink et al., 1985) have used this technique to study cochlear blood flow and have shown that the output varies in an expected manner following various experimental manipulations. It has been shown in fluid model studies that the maximum sensitivity of a laser Doppler instrument occurs at

a distance of approximately 0.6 mm from the tip of the probe (Nilsson et al., 1980). Although this distance will vary in vivo according to the composition of the tissue being studied and the characteristics of the flow probe (Nilsson et al., 1980), it allows an estimate of the location of the vascular beds in the cochlea that are contributing to the flow signal. The vessels of the lateral wall (i.e. the radiating arterioles, collecting venules and vascular beds of the spiral ligament and stria vascularis) and the basilar membrane lie within a distance approximately 1 mm from the surface of the bony cochlear wall (Pers. Observations) and the tip of the probe. These vascular beds thus may be providing the greater proportion of the signal in each cochlear turn than the vessels of the modiolus.

During the early course of these experiments it was noted that the laser Doppler flow output increased and decreased rapidly with the onset and offset of an intense pure tone stimulus. This increase in the flow signal during sound stimulation is also seen post-mortem in a generally similar fashion to the ante-mortem response, which demonstrates that it is not a real indication of flow. Further studies are being undertaken to determine the source of this artifact (Thorne and Nuttall, in preparation). The artifact prevents measurement of flow during high intensity exposure and thus it was necessary to turn the sound off in order to determine the extent of blood flow alterations. It was assumed that any alteration in cochlear blood flow caused during the sound exposure was present also during the 1 min measurement period. Since no significant changes in blood flow were observed during this 1 min measurement interval, this would seem to be a valid assumption. The exposure frequencies in the present study were selected to correspond tonotopically to the position of the laser Doppler probe on the first and second turns according to the place-frequency map for the guinea pig (Wilson and Johnstone, 1975; Cody et al., 1980). The 4 kHz tone puts the stimulus at the junction between the first and second turns which was on the basal aspect of the area covered by the probe.

The demonstration of a decrease in cochlear blood flow, which seems to be specific to the basal turn, is a significant finding. Maass et al. (1978), using the hydrogen clearance technique, found a similar decrease in blood flow after broad band noise (115 dB) in the guinea pig. However, the result is in contrast to a finding of Prazma et al. (1983) that blood flow increased, as shown by the microsphere technique, in the basal turn of the gerbil cochlea after a similar wide-band noise exposure as used in the present study (10–40 kHz, 113 dB SPL, 13 min). The conflicting findings may reflect a species difference or could be due to the techniques used. Unfortunately, in the study of Prazma et al. (1983) results were based on very small numbers of microspheres and this may have increased the error of the measurements. Hultcrantz (1979) and Hultcrantz et al. (1979), also using the microsphere method, were unable to find any alterations in blood flow through the cochlea of the rabbit and cat, respectively, during short duration (6 min) white-noise exposures of high intensity (120 dB). That the exposures were not of sufficient duration to produce a change in cochlear blood flow in these latter studies is suggested by our data showing the sound exposure produced only modest decreases in this measure following 10 min of exposure. It may be, also, that the changes, as seen in the present study, are regional and the proportional change in cochlear blood flow may have been too small to have been measured by the microsphere technique when it is used to determine total cochlear blood flow.

Our results are in line with many of the histological studies which have found significant morphological alterations in the cochlear vasculature that have been interpreted as representative of a decrease in blood flow during noise exposure (Hawkins, 1971; Vertes et al., 1979, 1982; Axelsson et al., 1981; Shaddock et al., 1985; Smith et al., 1985). These changes were found to occur predominantly in the vessels of the lateral wall. Unfortunately, it is not possible to determine the location of the vascular changes responsible for the decreased flow in the present study but perhaps they are similar to those seen in the histological studies (i.e., primarily located in the lateral wall). The decrease in cochlear blood flow that we have observed could be mediated by a variety of mechanisms. This decline is not associated with a change in blood pressure so is thus not a reflection of a general effect of noise on the cardiovascular system. Instead, it may be due to either the in-

fluence of the sympathetic system, which is known to decrease cochlear blood flow in the cat (Hultcrantz et al., 1977) or the release of humoral factors, such as prostaglandins, within the cochlea or direct mechanical trauma during the noise exposure. It is very interesting to note that the amount of prostaglandins in the cochlear fluids has been shown to increase substantially after noise exposure (Escoubet et al., 1985; Jung et al., 1986) since some types of prostaglandins have been shown to have vasoconstrictive properties (Horrobin, 1978). The alterations could occur as a secondary change to pathological alterations to the cells of the stria vascularis or spiral ligament as has been noted in several studies (Duvall et al., 1974; Santi and Duvall, 1978; Hukee and Duvall, 1985). The flow changes seen in the present study do not recover within the early portion of the post-exposure period which implies that they are not due to transient mechanisms. The reason that the flow changes seem to be restricted to the first cochlear turn is not clear, but the findings suggest that at least there are regional differences in the response of the cochlear vasculature to noise exposure.

It is important to note that an increase in cochlear blood flow was not observed after any of the exposures. Increased acoustic stimulation has been shown to cause greater metabolic activity in the mouse cochlea (Canlon and Schacht, 1983), gerbil cochlea (Canlon and Schacht, 1983; Ryan et al., 1984), and guinea pig cochlea (Schacht, Pers. Commun.) as measured by the deoxyglucose method, at least for moderate intensities of sound. However, above 85–105 dB SPL the uptake of labelled deoxyglucose in the mouse cochlea shows some decline. The results of the present study indicate that, at least in anesthetized animals, there is no increase in blood flow concomitant with the period of greater metabolic demand. It may be that the decline in blood flow observed could be responsible for the subsequent decrease in labelled deoxyglucose uptake seen at higher sound intensities.

A number of mechanisms have been postulated to explain the damage to the cochlea from noise exposure. It has been suggested that some damage, such as the rupture of the organ of Corti, its separation from the basilar membrane (Spoendlin, 1976), and fracture and displacement of hair cell stereocilia (Thorne et al., 1986) following high intensity exposures may be the result of excessive mechanical stress on the cochlear partition. Damage as the result of more prolonged, lower intensity exposures has been suggested to arise from the exhaustion of essential metabolites (Lim and Melnick, 1971) or a decrease in blood flow (Misrahy et al., 1958; Hawkins, 1971). Bohne (1976) has suggested also that the entrance of endolymph into the organ of Corti following damage to the reticular lamina may enhance hair cell degeneration following exposure. The present study confirms that cochlear blood flow does decrease following noise exposure, but comparison with the functional results bring into doubt the relevance of these changes in the development of cochlear injury. Apart from some of the 90 dB SPL exposures, animals exposed to loud sound, particularly the low frequencies, had some loss of cochlear function as measured by the CAP, but often showed no change in cochlear blood flow. Thus, although blood flow in the first turn was found to decrease with noise exposure it may not be causally related to the initial noise-induced cochlear injury. Carbogen (95% O_2 : 5% CO_2) breathing (Brown et al., 1982) and Dextran 40 infusion (Kellerhals, 1972) have been shown to reduce the extent of noise-induced cochlear damage in the guinea pig, possibly by improving blood flow in the cochlea during the noise exposure. Such data suggest that there may be some residual effect of cochlear blood flow in noise-induced injury which should be investigated further.

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References

Axelsson, A., Vertes, D. and Miller, J.M. (1981) Immediate noise effects on cochlea vasculature in the guinea pig. Acta Oto-Laryngol. 91, 237–246.

Bohne, B.A. (1976) Mechanisms of noise damage in the inner ear. In: Effects of Noise on Hearing, pp. 41–68. Editors: Henderson, D., Hamernick, R.P., Dosanjh, D.S. and Mills, J.H. New York, Raven Press.

Bonner, R. and Nossal, R. (1981). Model for laser Doppler measurements of blood flow in tissue. Appl. Optics. 20, 2097–2107.

Brown, J.J., Vernon, J.A. and Fenwick, J.A. (1982). Reduction of acoustically induced auditory impairment by inhalation of carbogen gas. 1. Permanent noise-induced cochlear damage. Acta Oto-Laryngol. 93, 319–328.

Brown, M.C., Smith, D.I. and Nuttall, A.L. (1983). The temperature dependency of neural and hair cell responses evoked by high frequencies. J. Acoust. Soc. Am. 73, 1662–1670.

Canlon, B. and Schacht, J. (1983). Acoustic stimulation alters deoxyglucose uptake in the mouse cochlea and inferior colliculus. Hear. Res. 10, 217–226.

Cody, A.R., Robertson, D., Bredberg, G. and Johnstone, B.M. (1980) Electrophysiological and morphological changes in the guinea pig cochlea following mechanical trauma to the organ of Corti. Acta Oto-Laryngol. 89, 440–452.

Dengerink, H., Miller, J.M., Axelsson, A., Vertes, D. and Van Dalfson, P. (1985). The recovery of vascular changes following brief noise exposure. Acta Oto-Laryngol. 100, 19–25.

Duvall, A.J., Ward, W.D. and Lauhala, K.E. (1974). Stria ultrastructure and vessel transport in acoustic trauma. Ann. Otol. Rhinol. Laryngol. 83, 498–515.

Escoubet, B., Amrallen, P., Feraary, E. and Tran Ba Huy, P. (1985). Prostaglandin synthesis by the cochlea of the guinea pig. Influence of aspirin, gentimicin, and acoustic stimulation. Prostaglandin. 29, 589–599.

Goodwin, P.C., Miller, J.M., Dengerink, H.A., Wright, J.W. and Axelsson, A. (1984). The laser Doppler: A non-invasive measure of cochlear blood flow. Acta Oto-Laryngol. 98, 403–412.

Hawkins, J.E. (1971). The role of vasoconstriction in noise-induced hearing loss. Ann. Otol. Rhinol. Laryngol. 80, 903–913.

Horrobin, D.F. (1978). Prostaglandins. Physiology, Pharmacology and Clinical Significance. Vermont, Eden Press.

Hukee, M.J. and Duvall, A.J. (1985). Cochlear vessel permeability to horseradish peroxidase in the normal and acoustically traumatized chinchilla: A reevaluation. Ann. Otol. Rhinol. Laryngol. 94, 297–303.

Hultcrantz, E. (1979). The effect of noise on cochlear blood flow in the conscious rabbit. Acta Physiol. Scand. 106, 29–37.

Hultcrantz, E., Linder, J. and Angelborg, C. (1977). Sympathetic effects on cochlear blood flow at different blood pressure levels. INSERM 68, 271–278.

Hultcranz, E., Angelborg, C. and Beausang-Linder, M. (1979). Noise and cochlear blood flow. Arch. Otol. Rhinol. Laryngol. 224, 103–106.

Jung, T.T.K., Juhn, S.D., Edlin, F., Morizono, T. and Ward, W.D. (1986). The effects of aspirin and noise exposure on the concentrations of prostaglandins in the perilymph, CSF and aqueous humor of chinchillas. Abstr. Assoc. Res. Otolaryngol. 9, 149.

Kellerhals, B. (1972). Acoustic trauma and microcirculation. An experimental and clinical study on the pathogenesis and treatment of inner ear lesions after acute noise exposure. Adv. Oto-Rhinol-Laryngol. 18, 91–168.

Kvietys, P.R., Shepherd, A.P. and Granger, D.N. (1985). Laser-Doppler, H_2 clearance, and microsphere estimates of mucosal blood flow. Am. J. Physiol. 249, G221–G227.

Lim, D.J. and Melnick, W. (1971). Acoustic damage of the cochlea: A scanning and transmission electron microscopic observation. Arch. Otolaryngol. 94, 294–305.

Maass, B., Baumgartl, H. and Lubbers, D.W. (1976). Lokale pO_2 Messungen mit Nadelelektroden zum Studium der Sauerstoffversorgung und Mikrozirkulation des Innenohres. Arch. Otol. Rhinol. Laryngol. 214, 109–124.

Maass, B., Baumgartl, H. and Lubbers, D.W. (1978). Lokale pO_2-pH_2 Messungen mit Mikrokoaxialnadelelektroden an der Bassalwidung der Katzencochlea nach akuter oberer zervikler Sympathectomie. Arch. Otol. Rhinol. Laryngol. 221, 269–284.

Miller, J.M., Marks, N.J. and Goodwin, P.C. (1983). Laser Doppler measurements of cochlear blood flow. Hear. Res. 11, 385–394.

Misrahy, G.A., Shinabarger, E.W. and Arnold J.E. (1958). Changes in cochlear endolymphatic oxygen availability, action potential, and microphonics during and following asphyxia, hypoxia and exposure to loud sounds. J. Acoust. Soc. Am. 30, 701–704.

Nilsson, G.E., Tenland, T. and Oberg, P.A. (1980). Evaluation of a laser Doppler flowmeter for measurement of tissue blood flow. IEEE Trans. Biomed. Eng. 27, 597–604.

Nuttall, A.L., Hultcrantz, E. and Lawrence, M. (1981). Does loud sound influence the intracochlear oxygen tension? Hear. Res. 5, 285–293.

Perlman, H.B. and Kimura, R. (1962). Cochlear blood flow in acoustic trauma. Acta Oto-Laryngol. 54, 99–119.

Prazma, J., Rodgers, G.K. and Pillsbury, H.C. (1983). Cochlear blood flow: Effect of noise. Arch. Otolaryngol. 109, 611–615.

Ryan, A.F., Woolf, N.K. and Sharp, F. (1984). Deoxyglucose uptake patterns in the auditory pathway: Metabolic response to sound stimulation in the adult and neonate. Assoc. Res. Otolaryngol. Abstr. 7:143.

Santi, P.A. and Duvall, A.J. (1978). Stria vascularis pathology and recovery following noise exposure. ORL 86, 354–361.

Shaddock, L.C., Hamernick, R.P. and Axelsson, A. (1985). Effect of high intensity impulse noise on the vascular system of the chinchilla cochlea. Ann. Otol. Rhinol. Laryngol. 94, 87–92.

Smith, D.I., Lawrence, M. and Hawkins, J.E. (1985). Effects of noise and quinine on the vessels of the stria vascularis: An image analysis study. Am. J. Otolaryngol. 6, 280–289.

Spoendlin, H. (1976). Anatomical changes following various noise exposures. In: Effects of Noise on Hearing, pp.

69–87. Henderson, D., Hamernick, R.P., Dosanjh, D.S. and Mills, J.H., eds. Raven Press, New York.

Thorne, P.R., Duncan, C.E. and Gavin, J.B. (1986). The pathogenesis of stereocilia abnormalities in acoustic trauma. Hear. Res. 21, 41–49.

Vertes, D., Axelsson, A. and Lipscomb, D.M. (1979). Some vascular effects of noise exposure in the chinchilla cochlea. Ann. Otol. Rhinol. Laryngol. 224, 97–101.

Vertes, D., Nilsson, P., Wersall, J., Axelsson, A. and Bjorkroth, B. (1982). Cochlear hair cell and vascular changes in the guinea pig following high level pure-tone exposures. Acta Oto-Laryngol. 94, 403–411.

Wilson, J.P. and Johnstone, J.R. (1975). Basilar membrane and middle ear vibration in the guinea pig measured by capacitive probe. J. Acoust. Soc. Am. 57, 705–723.