Characteristics of microwave-induced cochlear microphonics

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Cochlear microphonics (CM) have been recorded from guinea pigs and from cats of differing body mass during irradiation by 918- and by 2450-MHz pulsed microwaves. Both horn applicators and a cylindrical waveguide exposure system were used to radiate the animals. The CM frequency and duration were similar irrespective of carrier frequency and mode of application. Parameters of the CM (except amplitude) were not influenced by orientation of the body axis to the electrical field or by pulse width of microwaves for pulses less than 30 μsec wide. The frequency of the CM correlated well with the longest dimension of the brain cavity and poorly with several dimensions of the head. Extrapolations of these animal findings to the human being indicates that the frequency of the microwave-induced CM in man should be between 7 and 10 kHz.

1. INTRODUCTION

In our previous investigations [*Chou et al.*, 1975, 1976, 1977], we have shown that with proper recording techniques, a cochlear microphonic (CM) can be recorded from guinea pigs and from cats during pulsed irradiation by 918-MHz microwaves. Recordings of the pulse-evoked CM indicate that the microwaves initiate mechanical events that activate the auditory system at the cochlear level. Other studies [*Foster and Finch*, 1974; *Lebovitz and Seaman*, 1977; *Lin*, 1977] provide additional evidence in support of such an electromechanical interaction, one that presumably involves thermal expansion, which would contradict an earlier hypothesis of direct neural stimulation [*Frey*, 1971].

In this paper, we present more data on the microwave-induced CM in an attempt to answer the following questions: What dimensional parameters of the skull determine the frequency of CM? Do 918- and 2450-MHz microwave pulses produce differing CMs? Is the CM waveform dependent upon the polarization of the electrical field? Does the CM change as a function of source of radiation? What is the threshold of the microwave-induced auditory response? What is the expected frequency of CM in the human being?

2. METHODS

Guinea pigs and cats of different body masses were anesthetized with pentobarbital sodium (35-40 mg/kg IP). Either the right or left bulla was opened and a fine (microwave transparent) carbon lead was placed against the round window and cemented to nearby bone. An indifferent electrode was connected to proximal tissue. The heads of the guinea pigs and small cats were then placed inside and radiated within a cylindrical waveguide [*Chou et al.*, 1975]. The inserted head was parallel to the electrical field of the TE_{11} mode waves in the waveguide. For the large adult cats, a 13 × 13 cm aperture-source was loaded with dielectric material and was used for the 918-MHz exposure; a standard horn applicator was used to apply 2450-MHz microwaves. All animals, their exposure systems, the microwave generator (Applied Microwave Laboratory PH 40K), and two power meters were enclosed in an anechoic chamber, an isolation procedure that minimized microwave artifact in physiological recordings. Conventional physiological amplifiers (gain 2×10^4, bandpass 1 Hz to 100 kHz) processed the CM signal. The animals were radiated intermittently for 1.5 minutes at a time by 918- or by 2450-MHz microwave pulses of 10-μsec duration (rise time less than 1 μsec) and 100-pps repetition rate at various peak-power levels below 10 kW. The responses were recorded on a magnetic tape system (Honeywell 7600) with a frequency response of 80 kHz. For recordings made using a 100-μsec time base, a Honeywell SAI-43A correlation and probability analyzer was used to enhance and visualize the induced responses. The averaged responses were then plotted by an x-y recorder on graphic paper.

Two types of dosimetric measurements were made to calculate the quantity of absorbed energy per pulse. The parameters are stated in terms of energy instead of power, since the CM response is produced by microwave pulses of the same energy for all pulses of durations less than 30 μsec [*Guy et al.*, 1975]. For the guinea pigs and small cats that were radiated in the cylindrical waveguide, the averaged absorbed energy per pulse was calculated by dividing the total energy of the microwave pulse by the mass of the head, since more than 99% of the microwave energy was absorbed by the head [*Chou et al.*, 1977]. In order to use existing thermographic data [*Johnson and Guy*, 1972], a 3.1-kg cat was held in a stereotaxic instrument and was radiated by microwaves from a square-aperture source that was located 8 cm from the occipital pole of the cat. For cats radiated with the head in close proximity to the applicators, dosimetric measures were not made since the major interest was to elicit a CM response of reasonably high amplitude.

In order to obtain dimensions of the skull, animals were decapitated after the radiation experiments; the mass of the heads was determined and soft tissues were then removed from the skull. The following measurements were then made -- for terminology, refer to *Crouch* [1969] and *Cooper and Schiller* [1975]:

Skull mass (without lower mandible)

Skull size: L = between incisors and lambdoidal ridge
W = between right and left outside squamous portions
H = between outside vertex and basisphenoid in cats and spenoid in guinea pigs

Skull thickness (at vertex)

Brain-cavity dimensions

Cat: L = between upper transverse ridge and base of *tentorium cerebelli*
W = between right and left interior of squamous portions
H = between interior of vertex and occipital bone

Guinea Pig: L = between cribriform plate and occipital bone
W = same as in cat
H = between inside vertex and sphenoid

Brain-cavity volume

Bulla size L X W X H

Cerebellar-cavity dimensions

Cat: L = between intersection of sagittal and lambdoidal suture and basisphenoid
W = between widest points of cerebellum
H = between *tentorium cerebelli* and margin of skull

Cerebellar-cavity volume

3. RESULTS

Typical microwave-induced CM responses are shown in Figure 1. These responses occurred in every animal that exhibited an acoustically induced CM that was greater than 0.5 mV in amplitude. The amplitude of the CM varied with the placement of the electrode but the time course of the response did not. Therefore, only the time course of the responses will be mentioned in the following discussion. We have shown previously that microwave-induced CMs and auditory neural responses are independent of the pulse width for pulses of duration less than 30 μsec [*Chou et al.*, 1975; *Guy et al.*, 1975]. After considering the energy per pulse and the lifetime of the microwave generator tubes, we chose 10 μsec for all the experiments.

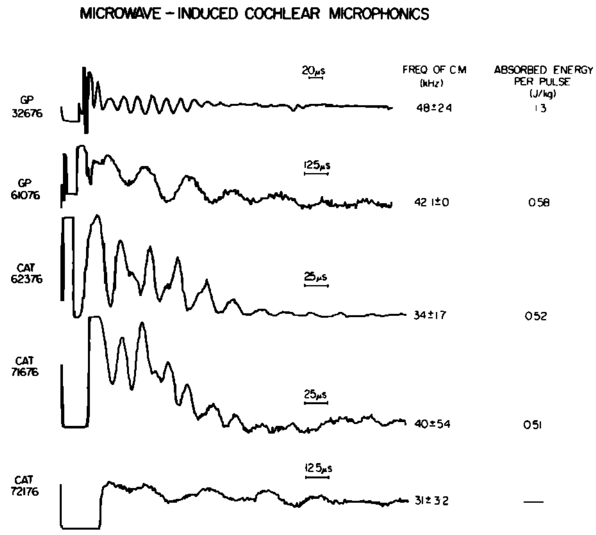

Fig. 1. Microwave-induced cochlear microphonics in guinea pigs and cats. Pulsed microwave: 918 MHz, 10 μs width.

There are two major differences in Figure 1. The frequencies of the CM are different and the waveforms of the CM of cats are more complicated than those of guinea pigs. The following experimental parameters were changed in an attempt to explain the above results.

Pulse width. Same frequency and duration of microwave-induced CM were produced by pulsed microwaves of 10, 5 and 1 μsec pulse width [*Chou et al.*, 1975]. The CM response is time-locked to the onset of the microwave pulses.

Polarization of electrical field. Figure 2 illustrates that there was no difference in the CM when the head was irradiated with the electrical field of TE_{10} mode waves either parallel or perpendicular to the anterior-posterial body axis.

Carrier frequency. Figure 3 shows that the same frequency and duration of CM were induced by 918- and 2450-MHz microwaves as delivered by horn applicators. The amplitude of the CM response was different because of the differing coupling efficiencies of the two horn applicators. When these horn applicators were used, it was necessary to place a cat's head in close proximity in order to record a detectable CM.

Horn applicator versus waveguide exposure system. For small cats exposed to the horn applicator and then to the cylindrical waveguide, the frequency and duration of CM were similar. The amplitude of the CM was much greater, however, when exposures were made in the cylindrical waveguide due to more efficient coupling of energy.

Body mass. Guinea pigs and cats of differing body

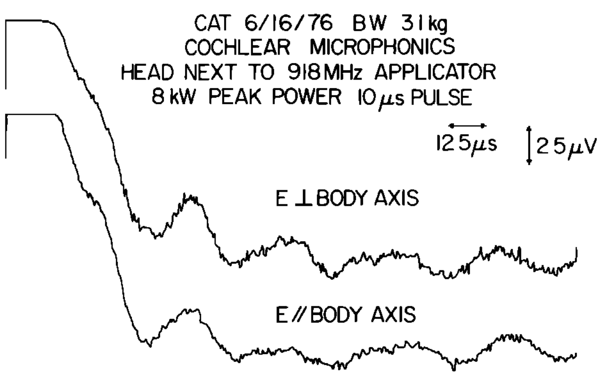

Fig. 2. Comparison of cochlear microphonics induced by pulsed microwaves at different polarizations of electrical fields.

mass were used. Tables 1 and 2 show the frequency of CM, the number of oscillations of CM, and $t_{1/e}$ (time required for the amplitude of the CM to drop to $1/e$). Pulsed microwaves of 10 μsec duration at 918 MHz were delivered at an averaged absorbed energy per pulse as indicated. Due to the large quantity of reflected power, which would limit the life of the microwave generator, exposure in the cylindrical cavity was made only once (GP 30675).

For guinea pigs, Table 1 shows that the larger the mass of the animal, the lower the frequency of the CM. Except for GP 32875, the number of oscillations decreased as body mass increased. The parameter $t_{1/e}$ varied between 31.6 and 55 μsec. Table 2 shows that the frequency of the CM varied between 29.6 and 32.5 kHz, with less than five oscillations, for adult cats exposed to the applicator. For kittens, (body mass < 2 kg) that were irradiated either in the cylindrical waveguide or by the horn applicator, the frequency varied between 31 to 40 kHz and the number of oscillations were between 5 and 10. There was no consistent relationship between the frequency of the CM and the body mass of the cats and kittens. It is also noted that the $t_{1/e}$ for cats is about two to three times longer than for guinea pigs.

Physical dimensions of the head. In an effort to isolate the variables that determine the CM, numerous measurements of dimensions of the animals' heads were made and are listed in Table 3. Note that as the body mass increases, so too does the head mass, skull mass, skull dimension, skull thickness and dimension of the cerebellar cavity; the brain cavity and bulla dimensions, however, increase only slightly. Plots of CM frequency versus each of the measured parameters as shown in Table 3 did not provide a consistent explanation for the variation in the frequency of CM in cats. However, the longest dimension in the brain cavity (for cats, that distance between the anterior orbital gyrus and the posterior tip of the posterior composite gyrus), shows a consistent relationship to frequency of the CM both for cats and for guinea pigs. As shown in Figure 4, it is clear that the greater the length of the brain cavity, the lower the frequency of the microwave-induced CM.

Concerning threshold of energy, Figure 5 illustrates the intensity-function for a small cat that was exposed in the cylindrical waveguide. This function is similar to that of a guinea pig studied by *Chou et al.* [1975]. For a larger, 3.1-kg adult cat, Figure 6 shows the relationship between N_1 (nerve response) amplitude and latency versus the peak value of absorbed energy per pulse. Since the amplitude of the CM was smaller than 5 μV under this exposure condition, the amplitude is not shown in the figure. For a 918-MHz plane wave that is incident on a spherical model of the brain (3 cm radius), the averaged specific absorption rate (SAR) in W/kg is about 3/8 of its peak SAR in the brain [*Johnson and Guy*, 1972]. As is seen in Figures 5 and 6, the efficiency of energy coupling in the cylindrical waveguide is about ten times higher than that of the aperture-source of radiation. The lowest energy required to induce a response (CM or N_1) was 10 mJ/kg peak in adult cats, 2.5 mJ/kg average in kittens, and 7.5 mJ/kg average in the adult guinea pigs. The peak absorbed energy density per pulse of guinea pigs as exposed in a cylindrical waveguide is about ten times higher than the averaged absorbed energy per pulse [*Chou et al.*, 1977]. The above results are consistent with our previous data for an estimated peak threshold of energy of 16 mJ/kg for hearing in human beings and an evoked response in the medial geniculate in cats of 10 mJ/kg. Comparable results have been reported by *Lebovitz and Seaman* [1977].

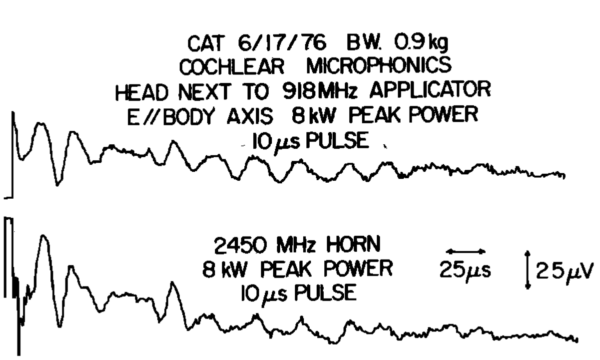

Fig. 3. Comparison of cochlear microphonics induced by pulsed microwaves at 918 and 2450 MHz.

4. DISCUSSION

Cochlear microphonics are electrical potentials that mimic the sonic waveforms of acoustic stimuli. An understanding of the microwave-induced CM should shed more light on the mechanisms of microwave-induced hearing. It was shown that the characteristics of CM (except amplitude) do not depend on carrier frequency, mode of application, field polarization and pulse width of the applied microwave pulses. Instead, the frequency of CM correlates well with the length of the brain cavity and poorly with other measurements made upon the head and the skull. These results provide more evidence that the microwave auditory effect is mechanical in nature.

TABLE 1. Characteristics of microwave-induced cochlear microphonics in guinea pigs.

Animal Number	Body Mass (kg)	Frequency ± SD (kHz)	No. of Oscillations	$t_{1/e}$ (μs)	Exposure Apparatus	Averaged Absorbed Energy per Pulse (J/kg)
GP 30675	∿ 0.4	∿ 50	8	--	Cylindrical Cavity	--
GP 32575	∿ 0.4	50 ± 0	11	--	Cylindrical Waveguide	1.4
GP 32675	∿ 0.45	48 ± 2.4	12	31.6	Cylindrical Waveguide	1.3
GP 32875	∿ 0.45	50 ± 0	5	--	Cylindrical Waveguide	1.3
GP 61076	1.10	42.1 ± 0	8	36.25	Cylindrical Waveguide	0.73
GP 61476	1.07	46.1 ± 2.5	10	55	Cylindrical Waveguide	0.8
GP 61576	1.13	39.2 ± 4	6	49	Cylindrical Waveguide	0.6

TABLE 2. Characteristics of microwave-induced cochlear microphonics in cats.

Animal Number	Body Mass (kg)	Frequency ± SD (kHz)	No. of Oscillations	$t_{1/e}$ (μs)	Exposure Apparatus	Averaged Absorbed Energy per Pulse (J/kg)
Cat 12076	2.9	∿ 33	3	--	Applicator	--
Cat 52176	3.2	31.7 ± 7.9	3	91	Applicator	--
Cat 52576	2.7	31.6 ± 4.3	5	--	Applicator	--
Cat 60376	2.6	32.5 ± 2.8	5	--	Applicator	--
Cat 60476	2.9	29.6 ± 1.3	4	140	Applicator	--
Cat 61676	3.1	30.5 ± 5.0	4	96.25	Applicator	--
Cat 61776	0.9	36 ± 3.3 35.5 ± 4.8	9 10	117 120	Applicator Cylindrical Waveguide	-- 0.8
Cat 62376	1.0	35 ± 2.7 34 ± 1.7	6 7	97.5 107.5	Applicator Cylindrical Waveguide	-- 0.52
Cat 71676	1.45	40 ± 5.4	8	100	Cylindrical Waveguide	0.51
Cat 71976	1.78	32.2 ± 1.7	5	110	Cylindrical Waveguide	0.43
Cat 72076	1.92	31 ± 3.0	8	---	Cylindrical Waveguide	0.51
Cat 72176	4.3	31 ± 3.2	4	137	Applicator	---

TABLE 3. Physical dimensions of animal heads.

ANIMAL Number	Body Mass (kg)	Head Mass (g)	Skull Mass (g)	Skull Dimensions L x W x H (cm)	Skull Thickness (cm)	Brain Cavity Dimensions L x W x H (cm)	Brain Volume (cc)	Bulla Dimensions L x W x H (cm)	Cerebellar Cavity Dimensions L x W x H (cm)	Cerebellar Volume (cc)
Guinea pig 61076	1.09	133	9.49	6.77 x 2.65 x 1.65	0.135	3.70 x 2.57 x 1.29	4.86	1.29 x 0.95 x 0.3		
Guinea pig 82476	0.57	70	6.39	6.18 x 2.48 x 1.63	0.08	3.46 x 2.26 x 1.27	4.6	1.17 x 0.88 x 0.26		
Cat 61676	3.13	304	28.2	9.6 x 4.28 x 3.5	0.195	3.55 x 3.96 x 2.85	22.4	1.89 x 1.24 x 0.68	3.01 x 2.39 x 2.84	6.8
Cat 62376	1.01	124	9.9	6.75 x 4.05 x 3.05	0.105	3.57 x 3.79 x 2.70	18.4	1.72 x 1.16 x 0.72	2.44 x 1.65 x 2.44	3.6
Cat 71676	1.45	152	13.5	7.24 x 4.13 x 3.08	0.1	3.4 x 3.86 x 2.70	18.4	1.66 x 1.14 x 0.73	2.62 x 1.94 x 2.80	5.1
Cat 71976	1.78	182	15.7	7.54 x 4.20 x 3.20	0.11	3.6 x 4.0 x 2.88	21	1.72 x 1.18 x 0.675	2.65 x 1.96 x 2.82	5.6
Cat 72076	1.29	154	13.8	7.31 x 4.11 x 3.22	0.1	3.6 x 3.87 x 2.84	20	1.69 x 1.16 x 0.65	2.59 x 1.92 x 2.69	5.0
Cat 72176	4.3	494	39.4	9.65 x 4.30 x 3.62	0.275	3.58 x 4.19 x 3.04	23.6	1.98 x 1.39 x 0.55	2.90 x 2.24 x 3.10	7.6
Human	---	---	847	18.4 x 14 x 12.4	0.8	16.8 x 11.4 x 13.0	1410			

Foster and Finch [1974] showed that a reflected pressure wave was measured in a lucite tank filled with KCL solution when exposed to pulsed microwaves. The time between pressure waves corresponded to the propagation time of acoustic waves in the solution. It is postulated that the induced pressure on the skull can be transmitted to the cochlea through bone conduction. Based on this hypothesis and the data from guinea pigs and cats, the extrapolated frequency for human beings lies somewhere between 7 and 10 kHz. Dimensions of the human skull are listed at the bottom of Table 3. Our results are consistent with theoretical predictions of *Lin* [1977].

In Figure 1, the shape of the CM induced in cats is more complicated than that of guinea pigs. The variation of the periods between CM peaks is also larger. These differences are probably due to differing brain-cavity structures in the two animals. In the cat, the cerebral cavity is separated from the cerebellum by a bony partition, the *tentorium cerebelli* (see Figure 7). The shape of the cerebral cavity is close to a quarter portion of a sphere. In the guinea pig (Figure 8) the brain cavity resembles an elongated ellipsoid and there

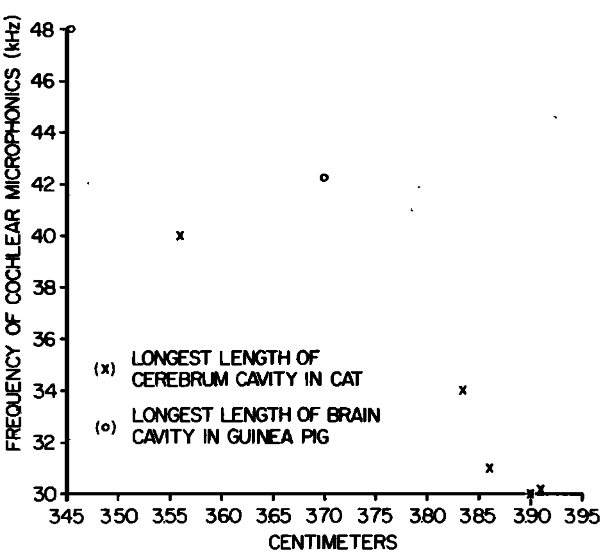

Fig. 4. Frequency of microwave-induced cochlear microphonics versus longest length in brain cavity.

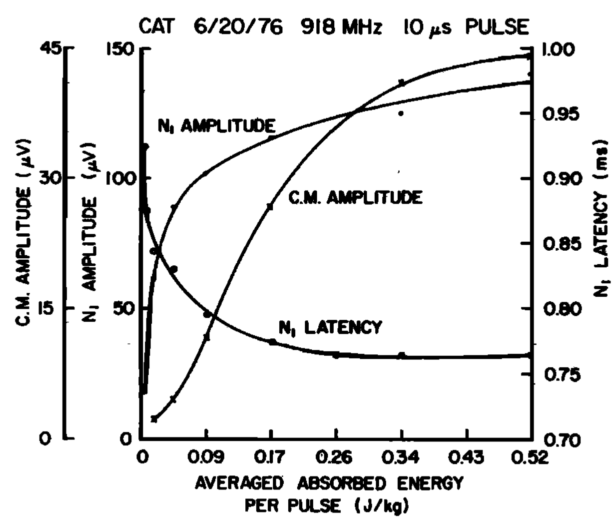

Fig. 5. Amplitude of microwave-induced CM and N_1, and latency of N_1, as a function of the averaged absorbed energy per pulse.

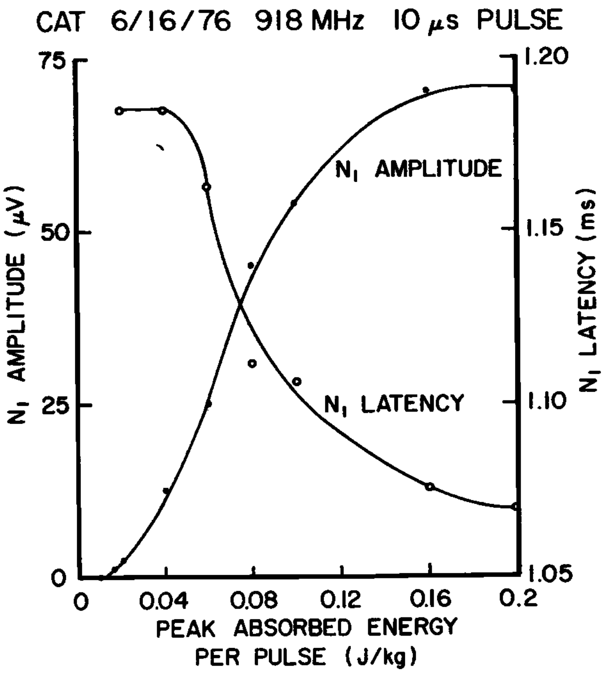

Fig. 6. Amplitude of microwave-induced N_1 and latency of N_1, as a function of the peak absorbed energy per pulse.

is no bony partition separating cerebrum from cerebellum. Thus, the temporal bone, where the cochlea is embedded, forms the wall of the cerebellar cavity in cats and differs from the whole-brain cavity of guinea pigs. The two separate compartments in cats may have caused the observed difference in waveforms.

The number of oscillations, as shown in Tables 1 and 2, seems to relate to the size of the head, presumably to the thickness of the skull. Although the number of oscillations depends on the intensity of microwave radiation, it appears to be similar for the two different exposure apparatus (cat 61776 and 62376). Based on the thickness of the human skull (0.8 cm at vertex), the number of oscillations may be below three for an absorbed energy per pulse that is less than 0.5 J/kg. The $t_{1/e}$ of guinea pigs is about half of that in cats. The implication of this difference is not clear.

Acknowledgments. This work was supported in part by the Bureau of Radiological Health Grant No. FD 00646-06; the Office of Naval Research Contract No. N00014-75-C-0464; General Medical Sciences Fellowship Award No. 1 F32 GM05681-01; and the Rehabilitation Services Administration Grant No. 16-P-56818. We thank Ms. Carrol Harris and Mr. Stephen Barnes for assistance.

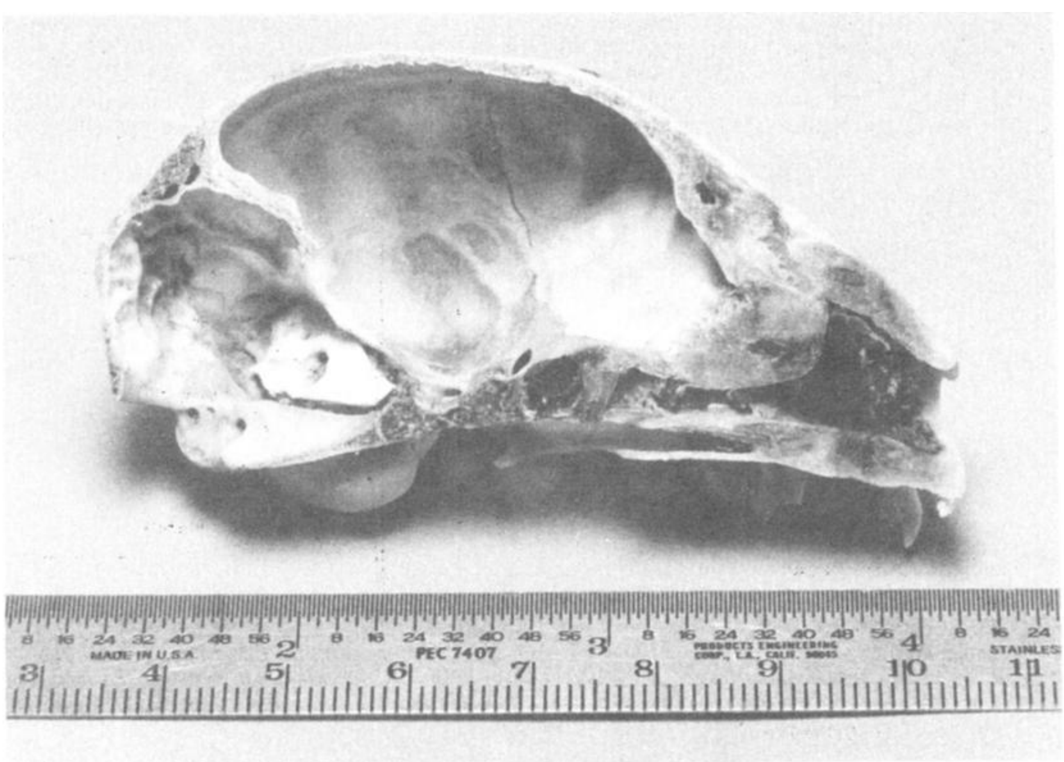

Fig. 7. Photograph of cat skull in sagittal plane.

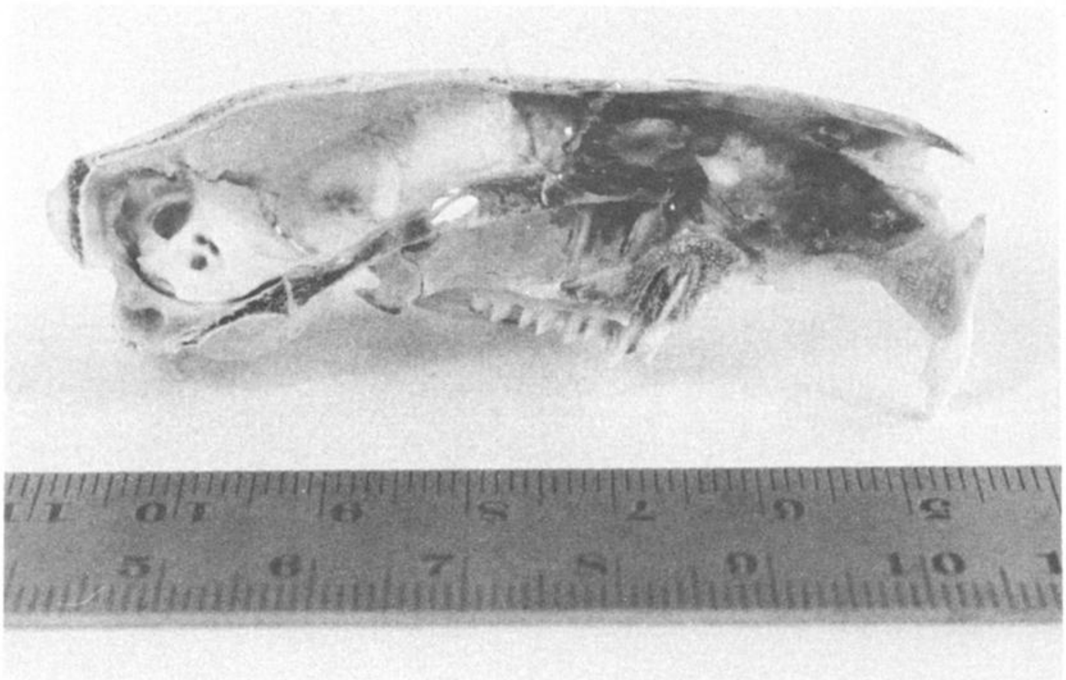

Fig. 8. Photograph of guinea pig skull in sagittal plane.

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