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Hearing and anatomy of the ear of the European hedgehog *Erinaceus europaeus*

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A major threat to the declining European hedgehog (*Erinaceus europaeus*) is road traffic. Devising methods to reduce the number of collisions would increase hedgehog welfare in an urbanized world and serve to protect this flagship species, and this goal might be advanced by an understanding of their hearing. This study investigates the auditory capabilities and anatomy of the ear of the European hedgehog. Using auditory brainstem response testing on 20 live hedgehogs from Danish wildlife rescue centres, we measured hearing thresholds across 4–85 kHz and found a peak sensitivity around 40 kHz, revealing that European hedgehogs can hear sound frequencies of at least 4–85 kHz. Complementary postmortem micro-CT scans enabled a detailed three-dimensional reconstruction of the inner ear, revealing small middle ear bones with a cochlear spiral of approximately 1.7 turns. Results show that hedgehogs can perceive a broad ultrasonic range, which provides important cues for directional hearing and may additionally function in prey detection and communication. These findings provide critical insights into hedgehog sensory biology and inform the potential development of ultrasonic repellents to mitigate traffic collisions and habitat disturbances, contributing to conservation strategies for this declining species.

1. Introduction

The concept of hearing and hearing capability has always intrigued people [1]. A very early example originates from Mesopotamia—from the Diagnostic and Prognostic Handbook—a text series, which is believed to originate in 1300 BCE. Tablet 3 of this series describes how ‘if he was injured on his head and, as a consequence, his hearing is affected (and) after the fever, before it returns and afflicts him’ [2].

Historically, research into animal acoustics has advanced from early behavioural observations to sophisticated neurophysiological and molecular methodologies, defining and describing the complexity of the central auditory system and the diversity of auditory systems in different species groups [1,3]. The purpose of investigating hearing in non-human animals extends beyond understanding sensory biology; it informs broader questions of intra- and interspecific communication and provides important insights into factors such as predator–prey interactions, foraging strategies and environmental adaptations. As anthropogenic noise increasingly disrupts natural soundscapes, understanding animal auditory capabilities also becomes relevant to the management of human–wildlife interactions and the planning of conservation efforts [4] directed at species such as the European hedgehog (*Erinaceus europaeus*), which is declining throughout its native range [5,6]. The hedgehog's decline appears to be driven by a multitude of factors [5], with roads and road traffic as major concerns estimated to cause a reduction in the hedgehog population of up to one out of three individuals every year [7–10], with a particular spike in mortality during the mating season associated with an increase in home range sizes [11,12]. Other machinery potentially exerting a negative impact on hedgehog numbers are garden strimmers [12,13] and robotic lawn mowers [14–16]. Therefore, measuring hearing in the European hedgehogs serves an additional, applied purpose, as the insight gained could be used to design ultrasonic sound repellents targeted at hedgehogs, potentially reducing the encounters between the species and cars and robotic lawn mowers [17]. Such devices should ideally emit sound frequencies that cannot be heard by humans or pets, which would require a target frequency above 65 kHz as the human hearing range is normally reported as 20–20 000 Hz [18], dogs 67–45 000 Hz [19,20] and cats 45–65 000 Hz [21,22] at a 60 dB re 20 μPa.

To our knowledge, the hearing of European hedgehogs has not yet been thoroughly investigated, but a few published articles on the hearing of different species of hedgehogs exist [23–32]. Table 1 provides an overview of previously published experiments on hedgehog hearing.

With this work, we aim to contribute to the growing field of auditory research on wildlife species through a comprehensive study of the hearing and ear anatomy of the European hedgehog. Our approach was to apply state-of-the-art methods, including ABR tests on live hedgehogs, micro-CT scans of a deceased individual and a virtual three-dimensional model showing the anatomy of the inner ear of the European hedgehog in detail.

2. Methods

The experiments (licence no. 2024-15-0201-01715) were conducted on 20 European hedgehogs, 10 males and 10 females (14 adults ≥1 year of age and six recently independent juveniles aged approximately 7–9 weeks) from two wildlife rescues in Denmark, constituting two experimental cohorts (table 2): cohort 1, near Slagelse, Denmark (55°24′37.6″ N, 11°22′04.6″ E) and cohort 2, near Aarhus, Denmark (56°10′44.5″ N, 10°10′40.3″ E).

Individuals were originally discovered by members of the public at different geographical locations situated within a radius of up to 50 km from a hedgehog rehabilitation centre. The hedgehogs had all been admitted into care, as sick, injured or orphaned, but were evaluated by licensed hedgehog rehabilitators as being ready for release back into the wild after successful rehabilitation, when participating in the experiments. We included a total of 20 individuals in the study with the intention to obtain a sample size allowing for individual variation in hearing capabilities but still providing a correct representation of hedgehog hearing. Furthermore, the sample size was influenced by the number of rehabilitated hedgehogs available for the tests. The hearing tests took place at night during the natural activity period of the hedgehogs from dusk until dawn [13]. Cohort 1 was tested on the night between 27 and 28 September 2024 at City Dyreklinik, Kronprinsessegade 76, Copenhagen, Denmark (55°41′18.3″ N, 12°35′08.9″ E). Cohort 2 was tested on the night between 11 and 12 June 2025 in the specialized sound laboratory in the Sound Communication and Behaviour group at the University of Southern Denmark, Campusvej 55, Odense, Denmark (55°22′06.6″ N, 10°25′35.5″ E). The study was not randomized nor blinded, as all animals underwent the same procedures.

(a) Housing and treatment

The hedgehogs were transported to the test facilities in boxes containing their own bedding material from the wildlife rehabilitation centre. Upon arrival, each hedgehog was placed in an unused cardboard box (55.6 cm × 37 cm × 34 cm) lined with a surgical drape sheet (Trixie Nappy, 60 cm × 40 cm) to soak up any water or urine. Cohort 1 received their own original straw bedding, placed in the box. Individuals of cohort 2 were offered their own cardboard housing box (30 cm × 20 cm × 30 cm), filled with bedding of straw and shredded newspaper. All bedding material originated from their respective housing facilities at the rescue centre, to reduce stress by using bedding with a familiar scent. A small water bowl was available throughout housing. Hedgehogs were kept in quiet rooms adjacent to the test laboratory with uncontrolled temperature, humidity and ventilation. Dark/light cycles followed the season's conditions.

Upon arrival, hedgehogs underwent a short clinical assessment (physical and behavioural observations, including the animals' general wellbeing, as well as signs of dehydration, stress and other transport damage), before being transferred to their housing facilities.

After recovery from anaesthesia, they were offered water, high-nutrition wet food (Hills AD) and kitten biscuits (Royal Canin Kitten) ad libitum. A final clinical health check was conducted before returning them to the rehabilitation centres the following day on 28 September 2024 and 12 June 2025, respectively. A few days later, they were released back into the wild.

(b) Clinical examination and anaesthesia

All the hedgehogs underwent a standard clinical examination including weighing, general observation with external examination of eyes, ears, paws, mouth, spines and skin, lymph nodes, auscultation of heart and lungs and pain evaluation through the pain face scoring on the grimace scale [33]. The ears were checked for signs of injury, bacterial or viral infection, excessive

Table 1. An overview of previously published research on hedgehog hearing.

					results		
species	**sample size**	**age**	**background**	**method**	**range (kHz)**	**best frequency (kHz)**	**reference**
Erinaceus europaeus	20 (results from 7 of these individuals were used to construct the audiogram)	6 juveniles and 14 adults (the 7 individuals were adults)	wild, after successful rehabilitation	auditory brainstem response (ABR), tABR with brief tone bursts	4-85 kHz and 16–60 kHz with thresholds < 60 dB re 20 µPa	40 kHz	[present study]
Atelerix albiventris	4	subadults (five months)	pets	behavioural audiogram	2–46 kHz at 60 dB	8 kHz at 21 dB	[24]
Erinaceus europaeus	66 (?): 33 tests based on 16 female–female communications and 17 male–male communications	unknown	most bred in captivity, a few came from the wild	vocalizations recorded with a UHER 4400 tape recorder, a Beyer M 69 omnidirectional microphone and a Sennheiser MKH 815 unidirectional microphone. Two sonographs (Kay 6061 B and Kay 8800) were used to obtain sonograms of the vocalizations	0–8 kHz	8 kHz at 21 dB	[27]
Hemiechinus auritus	4 (20)	adults	wild	microelectrode mapping, with electrodes inserted into the auditory cortex of the brain, and short clicks at 70 dB	'best frequencies' between 1 and 36 kHz	9.3–9.7 kHz	[29]
Hemiechinus auritus	unknown	litter(s?) of hoglets	bred in captivity	measuring their whistle sounds (chirps) with a Holgate Transducer. The mother reacted to the chirps	42–90 kHz	50 kHz	[30]
Hemiechinus auritus	2	adults	wildborn	behavioural audiogram, measured by the cessation of licking when sound is heard	0.250–45 kHz at 60 dB, 0.125–60 kHz at 80 dB	8 kHz	[28]
Erinaceus roumanicus	5	parents and 3 juveniles of eight weeks	unknown	behavioural response to a sound generator playing sounds of up to 100 kHz	no response at all	no response at all	[25]
Erinaceus roumanicus	6	different ages	unknown	behavioural response defined as flexing of spines creating a sonograph up to 24 kHz (which was the limit of the equipment), and producing sounds like lip thrills, the	up to 24 kHz		[25]

(*Continued.*)

Table 1. (*Continued.*)

species	sample size	age	background	method	results		reference
					range (kHz)	best frequency (kHz)	
				tapping of iron against a glass container, the striking of thin sheet metal with glass, the snapping steel scissors, operating a light switch, dropping keys on a table			
Erinaceus europaeus	3	1 adult and 2 subadults	bred in captivity	behavioural audiogram, using a dog whistle (Galton's whistle) and an Atlas-Audiometer, measuring twitching of the hedgehog's ear to record if a sound was heard	0.064–18 kHz	2–8 kHz	[26]
Erinaceus amurensis (?)	14	unknown	unknown	behavioural audiogram, measured by using a Galton's whistle (dog whistle), blown at different distances from the ear of the hedgehog, causing a jerk of the head. Second test: electrical stimulation of the 8th cranial nerve and the acoustic tubercle to determine the afferent arc. Third test: surgical removal of the cerebral cortex and thalamus, and later, the midbrain to measure any behavioural reactions (head jerk or ear swing) to the sound of Galton's whistle: no reaction to sound after the midbrain was removed	7.6–84 kHz	20 kHz	[23]

Table 2. Overview of the number of individuals included in each experimental cohort.

	males		females		total
	young	adult	young	adult	
body weight	280–545 g	690–1385 g	440–460 g	565–1225 g	
cohort 1	4	2	2	2	10
cohort 2	0	4	0	6	10

amounts of cerumen or ear mites, which could affect the test results. Only individuals with healthy ear canals were included in the tests. When assessed ready for anaesthesia, the hedgehogs were treated with the following medical drugs:

Cohort 1: meloxicam (Metacam 5 mg ml^{-1}) subcutaneously for pain relief with a dosage of 0.1 ml kg^{-1} equivalent to 0.5 mg kg^{-1} due to the placement of electrodes. In some cases, Diazedor (diazepam 5 mg ml^{-1}) was administered subcutaneously to prolong the anaesthesia with a dosage of 0.1 ml kg^{-1} or equivalent to 0.5 mg kg^{-1}. A single dose of alfaxalone (Alfax Multidose Vet 10 mg ml^{-1}) was administered subcutaneously for anaesthesia with a dosage of 1 ml kg^{-1} equivalent to 10 mg kg^{-1}.

Cohort 2: meloxicam (Loxicom 1.5 mg ml^{-1}) per oral for pain relief with a dosage of 0.35 ml kg^{-1} equivalent to 0.5 mg kg^{-1}. A combination of midazolam (Midaxolam Hameln 5 mg ml^{-1}) and alfaxalone (Alfax Multidose Vet 10 mg ml^{-1}) was administered subcutaneously for anaesthesia with a dosage of 1 ml kg^{-1} equivalent to 10 mg kg^{-1} for alfaxalone and 0.1 ml kg^{-1} and 0.5 mg kg^{-1} for midazolam.

Once anaesthetized, an oxygen mask (Midmark, 5 cm in diameter) was placed on the nose and mouth of the individual, with an oxygen pressure of 1000 mmHg and a flow of 1 l min^{-1}. A veterinary pulse oximeter (M3 Series Handheld Pulse Oximetry Monitor model M3T TTM01) with a built-in rectal thermometer and a blood oxygen probe for measuring heart rate and oxygen saturation monitored the vital signs of the hedgehog during general anaesthesia. The blood oxygen probe was attached to the right front paw, and the thermometer was placed in the rectum. Temperature (°C), heart rate (beats per minute), oxygen saturation (% O_2) and respiration rate (breaths per minute) were recorded approximately every 5–10 min. Eye drops (Aptus SentrX Eyedrops) were also administered for the hedgehog to reduce the risk of ophthalmic complications. The hedgehogs were placed on heat mats (SnuggleSafe, heated for 5 min in a microwave at 900 W) during the tests. Anaesthesia ranged between 30 and 45 min for cohort 1 and 45–60 min for cohort 2, with between 32 and 87 min from injection of the anaesthetic to awakening (electronic supplementary material).

When the experiment was completed, the hedgehogs were placed on heat mats (SnuggleSafe, heated for 5 min in a microwave at 900 W) and monitored closely during recovery. Once they recovered and regained reflexes, they were offered food (see electronic supplementary material for results and individual treatments).

(c) Hearing tests

(i) Setup for cohort 1

Recordings were made in a custom-made medium-density fibreboard soundproof box lined with aluminium foil inside for electrical shielding and covered by 40 mm acoustic foam. The internal volume of the box was 80 cm × 60 cm × 60 cm. A loudspeaker (Ultrasound Dynamic Speaker, Avisoft, FRG, frequency response flat within 7 dB up to 90 kHz) was mounted on the side of the box facing the left ear of the hedgehog at approximately 25 cm distance. The signal to the Avisoft speaker was generated by an RX6 multiprocessor (Tucker-Davis Technologies (TDT), Alachua, FL, USA) and amplified by a power amplifier (DD8, Xelex, S).

(ii) Set-up for cohort 2

Recordings were made in an audiometric cabin (T-cabin, CA TEGNÉR, S) on a table built from consecutive layers of flagstone and mineral wool to minimize noise and vibrations from the floor. The walls inside the cabin were padded with sound-absorbing wedge tiles (Classic Wedge 30, EQ Acoustics, UK), and the loudspeaker, a Vifa Speaker, frequency response flat within 10 dB up to 90 kHz (Avisoft, FRG), was placed at an angle to the walls to minimize sound reflections. The hedgehog was placed on the table approximately 60 cm from the loudspeaker. The signal from the RX6 multiprocessor was amplified by a Portable Ultrasonic Power amplifier (Avisoft, FRG).

(d) Auditory brainstem response

Measurements of the ABR followed the same procedure for both cohorts. Summated potentials from the auditory nerve and brainstem were recorded with three subdermal electrodes (Disposable Needle Electrode, 0.4 mm, 12 mm, Cephalon, DK). The two differential electrodes were placed at the mastoid (behind the pinna) and in the vertex and a ground electrode was placed in the shoulder. The electrode signal was amplified by a low-impedance headstage and a four-channel pre-amplifier (TDT RA4/PA4). The signal was digitized at a sample rate of 24 424 Hz and recorded on a mobile processor (TDT RM2) controlled

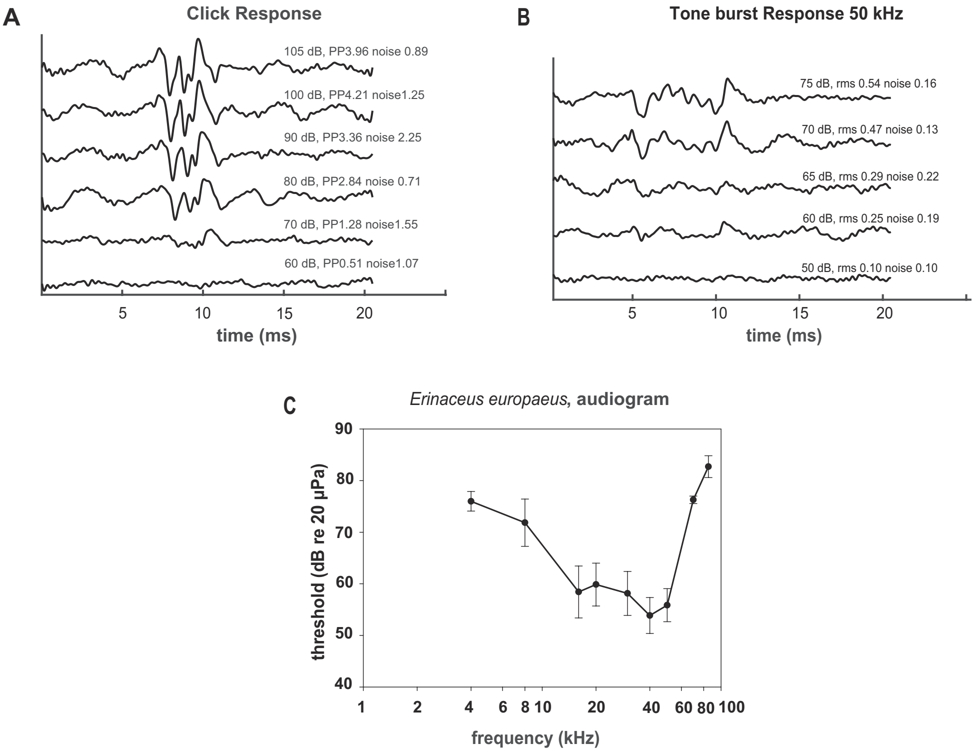

Figure 1. Click responses, tone burst responses and an audiogram. (A) Traces show an example of the response to a transient stimulus (impulse, duration 20 µs) at different stimulus levels. (B) Traces show an example of response to a 5 ms tone burst at 50 kHz presented at different levels. (C) Audiogram based on average ABR thresholds of seven hedgehogs stimulated with 5 ms tone bursts. Stimulus frequency is on a log scale.

by a PC, also controlling stimulus generation on the RX6 and storing data. Each recording consisted of 400 averages, and the averaged data for each experiment were divided into two batches and stored on the PC. Stimuli generated on the RX6 multiprocessor were brief transients (20 µs) and 5 ms tonebursts at frequencies from 4 to 85 kHz played at a sample rate of 192 kHz. Stimulus generation and data collection were controlled by custom-made software (QuickABR-burst [34]). Data for a complete audiogram could be collected within 1 h, but the durations of the tests depended on the duration of the anaesthesia.

(e) Calibration

The system was calibrated by a Free-field ¼″ microphone (Brüel & Kjaer 4939 ¼″ microphone, flat frequency response) and a B&K 2670 preamplifier. The microphone was powered by a Dual Microphone Supply (Brüel & Kjaer Type 5935) and placed at the left ear of the hedgehog. It was calibrated with an acoustic calibrator (Brüel & Kjær, Type 4231). Calibration was controlled by custom-made software (QuickABR-burst).

(f) Data analysis

The averaged ABR recordings were band-pass filtered (200–3000) Hz. The recordings were evaluated by measuring the mean of the two batches (the signal) compared to the difference between the batches (the noise) [35]. We compared the root mean square (rms) value to the noise rms in the same interval defined as the effective or average level of sound in the interval 3–13 ms after measurement onset. Signal and noise rms were calculated from each stimulus presentation, and the threshold was calculated from a linear regression of signal rms versus stimulus amplitude for each stimulus frequency as the intercept of the line with the average rms noise.

(g) A micro-computed tomography model of the European hedgehog ear

For the purpose of describing the anatomy of the European hedgehog ear, the head of a euthanized, adult European hedgehog was scanned using micro-CT at Aarhus University, Palle Juul-Jensens Blvd 99, Aarhus, Denmark (56°11′20.0″ N, 10°10′25.6″ E). The hedgehog had been admitted into care on 29 May 2025 due to a recent and severe leg injury caused by entrapment in a rat trap. The damage to the leg, a complex fracture in the elbow joint, was deemed too comprehensive to heal, and the hedgehog was euthanized with carbon dioxide for animal welfare reasons. The hedgehog did not show any signs of infection and had no head injuries. The euthanized hedgehog was brought to the lab at Aarhus University. Here, the head was dissected off and skinned and immersion fixed for one week in 4% formaldehyde solution (phosphate buffered at pH 7.4). The entire head was micro-CT scanned using a CoreTOM system (TESCAN GROUP, Brno, Czech Republic) equipped with an integrating detector and using the following parameters: X-ray tube voltage = 120 kVp, X-ray tube power = 20 W, integration time = 135 ms, spatial resolution = 0.02 mm isotropic, number of averages = 6 and acquisition time = 6 h. A bone mineral calibration

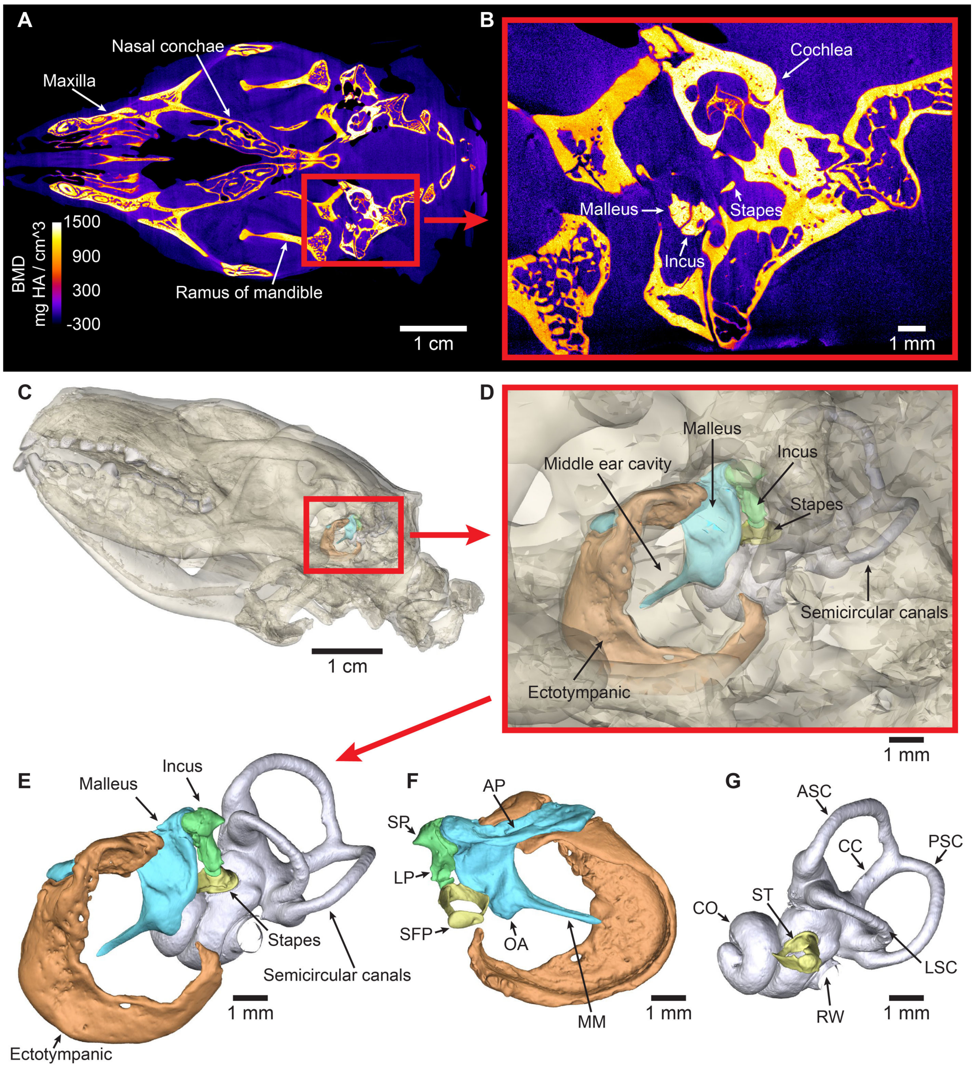

Figure 2. BMD and micro-CT reconstructions of the European hedgehog skull and ear bones. (A) Annotated virtual coronal micro-CT section of the entire head of a European hedgehog. (B) Magnification of the left ear. Pixel values were converted into BMD values in milligrams of hydroxyapatite (HA) per cubic centimetre. Ear bones are slightly denser than the remaining bones in the skull. (C) Ventrolateral view of a micro-CT reconstruction of the hedgehog skull. (D) Magnification of the left ear. Bones not associated with the ear are rendered semi-transparent. (E–G) Annotated reconstructions of the middle and inner ear bones viewed from different angles. AP, anterior process of malleus; ASC, anterior semicircular canal; CC, crus commune; CO, cochlea spiral; LP, long process of incus; LSC, lateral semicircular canal; MM, manubrium of malleus; OA, orbicular apophysis of malleus; PSC, posterior semicircular canal; RW, round window; SFP, stapes footplate; SP, short process of incus; ST, stapes.

phantom (four rods containing 0, 50, 200 and 800 mg hydroxyapatite cm^{-3}, respectively) was positioned next to the head to allow for the conversion of arbitrary image values to values of bone mineral density (BMD). Subsequently, a high-resolution local tomography scan using extended field-of-view was acquired at the level of the ear with the following parameters: X-ray tube voltage = 120 kVp, X-ray tube power = 15 W, integration time = 180 ms, spatial resolution = 0.009 mm isotropic, number of averages = 4 and acquisition time = 9 h.

To generate an interactive three-dimensional model of the hedgehog ear, the head and ear scans were co-registered and skeletal components were digitally segmented using the imaging software Amira (Thermo Fisher Scientific) v. 5.3.3. Extracted surfaces were exported in the Wavefront format (.obj) and the model was assembled in Adobe Acrobat 3D v. 8 Toolkit, and an interactive PDF model was generated in Adobe Acrobat 3D v. 8.

3. Results

(a) Hedgehog hearing

A total of 20 European hedgehogs was tested and responded to transients and tone bursts. The test trial lengths were defined by the duration of the anaesthesia (range = 19 and 62 min). Seven full audiograms were produced (all adult individuals, four females and three males). An example of a response to a transient at different stimulus levels (figure 1A) and to a tone burst (50 kHz; figure 1B) is illustrated below. Figure 1C shows the average audiogram based on data from seven animals from cohort 2. Only cohort 2 individuals are included as most hedgehogs from cohort 1 woke up before the audiogram was completed. The audiogram shows thresholds from 4 to 85 kHz, with the highest auditory sensitivity around 40 kHz. The medians of female and male audiograms were similar (electronic supplementary material).

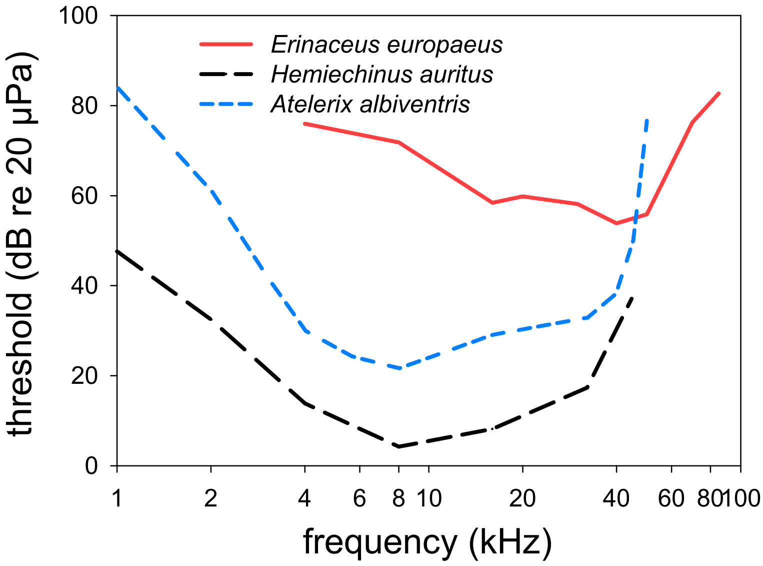

Figure 3. Audiograms for three species of hedgehogs, comparing behavioural audiograms of *H. auritus* [28] and *A. albiventris* [24] to our present ABR data from *E. europaeus*.

(b) Anatomy of the ear of the European hedgehog

Middle and inner ear anatomy of the European hedgehog was largely in agreement with the description of the African pygmy hedgehog (*Atelerix albiventris*) by Heffner *et al.* [24]. As in *A. albiventris*, the ectotympanic of the European hedgehog was partly overlapped by the tympanic wing of the basisphenoid bone, and it was associated with the alisphenoid and petrosal bones dorsolaterally. Due to the loose ligamentous attachments of these bones, there is no complete bulla in the European hedgehog. The bone mineral content of the ear-associated bones was slightly higher than other cranial bones, appearing denser on virtual micro-CT sections (figure 2A,B). Specifically, BMDs were: ectotympanic: 2071 mg HA cm^{-3}, malleus: 2090 mg HA cm^{-3}, incus: 2111 mg HA cm^{-3}, stapes: 1900 mg HA cm^{-3}, respectively.

From the micro-CT acquisition, a three-dimensional interactive model of the ear anatomy was constructed (figure 2C–G; see Data accessibility for model download instructions). The three middle ear bones were small, specifically: malleus: 2.65 mm^3, incus: 0.56 mm^3, stapes: 0.24 mm^3. The values are 1.4–2 times higher than the measurements by Henson [36] due to the different methodology. Using the densities reported above the resulting mineral mass of the three ossicles is 5.54, 1.18 and 0.456 mg, respectively. The ectotympanic and malleus were partly synostosed, however, seemingly less so than in *A. albiventris* [24]. The stapes had a footplate area of 0.46 mm^2. The cochlea displayed 1.7 turns following the method described by Ekdale [37]. The semicircular canals were relatively wide as described for *A. albiventris* [24], but in opposition to the generally thin representation of semicircular canals across many orders of placental mammals by Ekdale [38].

4. Discussion

We measured responses to sound from 4 to 85 kHz in the European hedgehog. Seven individuals experienced the full test range, and the remaining 13 woke up prematurely from the anaesthesia, securing only a fraction of the full sound range. Individuals who received diazepam injections to prevent premature awakening from anaesthesia were all very active prior to testing. The sensitivity was highest at 40 kHz and declined above 50 kHz. The lowest average threshold was at 54 dB sound pressure level. These thresholds are considerably higher than reported earlier for the African pygmy hedgehog (*A. albiventris* [24]) and the long-eared hedgehog (*H. auritus* [28]) (figure 3). However, since the previous measurements are behavioural thresholds, which normally are at least 20–25 dB below ABR thresholds [39], the lowest thresholds of the European hedgehog are probably comparable to the lowest thresholds of the African pygmy hedgehogs [24]. Differences in thresholds may reflect the use of anaesthesia and the short-duration tone bursts (5 ms) used here compared to behavioural studies (400 ms for *Atelerix* and 10 s for *Hemiechinus*), both of which may lower sensitivity.

All methods have limitations, see for example, Brittan-Powell *et al.* [40] for a discussion of the ABR approach in comparison to behavioural testing. In the case of the European hedgehog, a wild-living and protected species prone to stress in long-term captivity [41],we considered the ABR method the only realistic approach, while also being the least invasive and most reliable under the circumstances described.

Whereas comparisons of thresholds may be difficult between behavioural audiograms and ABR audiograms, the shapes of the audiograms are usually comparable [38]. Thus, the frequency range of *Erinaceus* seems to be wider than in *Atelerix*, but comparable to the hearing range of similar sized mammals with microtype ears, for example, long-eared hedgehog (*H. auritus*), opossum (*Didelphis virginiana*) or Norway rat (*Rattus norvegicus*) (table 1 in [24]). As we measured responses to a pre-defined spectrum, we cannot rule out the possibility that the European hedgehog can hear sounds with frequencies above our set threshold of 85 kHz.

The middle ear is very similar to the middle ear of *Atelerix*. Like *Atelerix*, the middle ears of *Erinaceus* and other hedgehogs belong to the ‘ancestral’ ear type [42], where the malleus has a relatively stiff articulation with the ectotympanic and the auditory bullae being partly open. The partial fusion of the malleus and ectotympanic increases the stiffness of the ossicular chain and contributes to the ultrasound sensitivity of mammals with 'ancestral' or 'microtype' ears [42,43].

Notable differences between *Erinaceus* and *Atelerix* are that the middle ear ossicles generally are heavier in *Erinaceus* than in *Atelerix* (malleus 2.11 mg, incus 0.67 mg and stapes 0.15 mg), corresponding to a ratio of 2–3 between the masses of the ossicles in the two species that roughly corresponds to the ratio of masses of the two species, suggesting an allometric scaling. Other differences are the shape of the incus, where the difference between the long and short process seems to be smaller, and that the malleus in *Erinaceus* is not synostosed to the ectotympanic, but connected via a fibrous connection [24], but whether these differences contribute to the increased high-frequency sensitivity in *Erinaceus* is unknown.

The results from this investigation show a potential for the development of targeted ultrasonic sound repellents to deter hedgehogs temporarily from potential dangers such as the particular models of robotic lawn mowers found to be hazardous to hedgehog survival, and more importantly, cars [7,11,14]. Work is underway to ensure more hedgehog-friendly robotic lawn mowers [14,15,16,44]. However, an ultrasonic sound repellent could greatly aid hedgehog conservation, given that road traffic is an increasing pervasive threat across the species' range. Designing sound repellents for cars to reduce the high number of road-killed hedgehogs enhances animal welfare and supports conservation of this declining flagship species. This procedure would include many steps such as understanding how hedgehogs react to ultrasound, which sounds they would find aversive, whether they would habituate to the sound and finally, whether the sound of the repellent would work over a distance long enough to give them the necessary time to escape the approaching cars.

The discoveries made in this research leave important questions to be answered. Like other mammals with microtype ears, the European hedgehog is sensitive to ultrasound. However, why have they evolved the ability to hear ultrasound? Do they, perhaps, use this ability in their hunt for the specific species of insects that produce ultrasonic sounds? We have not investigated sound localization in European hedgehogs, but it is likely that ultrasound sensitivity is important for directional hearing in this species, as has been proposed for *A. albiventris* [24]. Furthermore, the vocalization of European hedgehogs appears to be rather limited, with only a few different sounds described, mostly serving as communication between mothers and offspring, and to express pain and distress [10]. This is perhaps not surprising, given the species' solitary and non-territorial behaviour [13]. It remains to be investigated whether a whole sound landscape of hedgehog communication would be unfolding if recorded in ultrasound, as seen in some other small mammals, such as mice [45]. Research to develop sound repellents is currently being planned by the team, and investigations exploring the possible ultrasonic communication in European hedgehogs have been initiated.

5. Conclusion

By testing the ABR of 20 European hedgehogs we found that they hear sounds between 4 and 85 kHz, with the highest auditory sensitivity around 40 kHz. Through micro-CT scans of a European hedgehog, we provided micro-CT reconstructions of the skull and ear bones of the European hedgehog, and an interactive three-dimensional model of the ear of the European hedgehog.

Ethics. The experiments were conducted in accordance with the licence provided by the Danish Animal Experiments Inspectorate (2024-15-0201-01715) in accordance with 2010/63/EU. We followed the 3R concept for ethical use of animals in research: we stopped data collection when we had obtained sufficient data (i.e. reduction), and we ensured that no animal suffered harm during the study through anaesthesia and analgesia (i.e. refinements). It was not possible to replace the studies with alternative methods (i.e. replacement), except that scans were performed on an already dead individual. All animals completed the tests without injury and were released back into the wild within a few days.

Data accessibility. Imaging data of the micro-CT imaged European hedgehog (catalogue no. ZMUC-M03-3856) head (20 µm resolution, 24.8 GB) and ear (9 µm resolution, 37.1 GB) are available from MorphoSource (https://www.morphosource.org/): project no. 000817860 (https://www.morphosource.org/projects/000817860?locale=en). An interactive three-dimensional model of the ear of the European hedgehog *Erinaceus europaeus* is available for download from Figshare [46] (14.7 MB). The PDF file can be opened in Adobe Reader and after the 3D function is enabled by left-clicking the preview, the model can be rotated, and individual layers can be turned on/off and made transparent.

Supplementary material is available online at [47].

Declaration of AI use. We have not used AI-assisted technologies in creating this article.

Authors' contributions. S.L.R.: conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, visualization, writing—original draft, writing—review and editing; D.W.M.: conceptualization, writing—review and editing; R.N.R.H.: conceptualization, data curation, investigation, methodology, writing—review and editing; H.M.T.: conceptualization, data curation, formal analysis, investigation, methodology, visualization, writing—review and editing; H.L.: conceptualization, data curation, formal analysis, investigation, methodology, visualization, writing—original draft, writing—review and editing; A.K.O.A.: conceptualization, data curation, investigation, methodology, writing—review and editing; J.C.-D.: conceptualization, data curation, formal analysis, investigation, methodology, visualization, writing—original draft, writing—review and editing.

All authors gave final approval for publication and agreed to be held accountable for the work performed therein.

Conflict of interest declaration. We declare we have no competing interests.

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