Assessment of the Effect of Natural and Anthropogenic Aquatic Noise on Vaquita (*Phocoena sinus*) Through a Numerical Simulation

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1 Introduction

Phocoena sinus (vaquita) is a small marine harbor porpoise endemic to the Gulf of California that is believed to be the most endangered cetacean in the world as reported by the International Union for Conservation of Nature (IUCN) red list (see Rojas-Bracho et al. 2008). Simultaneous use of the same habitat by fishermen and *Phocoena sinus* has led to the precipitous decline of the porpoise. *Phocoena sinus* is easily entangled in fishing nets, resulting in drowning.

Our challenge was twofold: first, to understand the pathway by which *Phocoena sinus* receives sound and second, whether *Phocoena sinus* should be able to detect nets using their echolocation system. Recently, research cruises have focused attention on recording sounds present in the *Phocoena sinus* habitat. We used numerical analysis to understand how sound propagates through the anatomy of *Phocoena sinus*. Finite element modeling (FEM) offers the capacity to simulate what happens when anatomic geometry interacts with sound pressure waves. An example of a similar application of FEM can be found in Cranford et al. (2008) where they constructed a numerical simulation of the acoustic pathways in the head of a Cuvier's beaked whale. This kind of simulation is valuable because marine mammal hearing is not fully understood and contradictory suggestions have been put forth to explain it. It is clear that toothed whales have a well-developed sense of hearing, probably as a result of selective pressures that compensate for the diminishing penetration of light in water. It is not yet clear how toothed whales detect, receive, filter, or amplify sounds.

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We focused our attention on simulating interactions with pinger sounds because they have been used in entanglement mitigation efforts around the globe with other porpoise species. It is worth emphasizing that the interaction between porpoise anatomy and high-frequency sounds has not been investigated previously.

2 Materials and Methods

We had access to two postmortem *Phocoena sinus* specimens thanks to the generosity of the Government of Mexico. The specimens were scanned using X-ray computed tomography (CT). The 3-dimensional image data provide a detailed map of anatomic structure, which is the starting point for building an acoustic simulation.

The material parameters needed for the isotropic constitutive equation are density, bulk modulus, shear modulus, and dynamic viscosity. The sample density can be mapped from the CT image using a conversion from the Hounsfield units. Because the dynamic viscosity is not available as a map of the Hounsfield units and needs to be estimated from the literature, we used data from Krysl et al. (2006) to assign representative average mechanical properties to tissues in the following groups: hard bone, soft bone, connective tissue, muscle, and acoustic fats/blubber.

2.1 Numerical Simulation

The CT data provide the anatomic geometry for the model: a voxel in the CT image corresponds to a hexahedral height-node finite element. No approximations or interpolation is made on the CT image resolution. For simplicity, the computational box is assumed initially at rest and unstressed. Such an assumption makes it easy to reconcile the boundary and the initial conditions. It also implies that the specimen and its bounding box are near the sea surface and that the system is not exposed to significant hydrostatic pressure. The three velocity components are prescribed along all the bounding surfaces of the computational box. In particular, these initial and boundary conditions correspond to plane sound waves propagating in the left-to-right direction (see Fig. 1), with an exponential ramp-up from a rest/unstressed state to full power within a fraction of a millisecond. In this paper, we consider a preliminary set of traveling sound waves of frequencies from 80 to 120 kHz directed along the line connecting the tip of the nose to the first vertebra of the animal. The subsequent step, which we will investigate in the future, is to consider different angles for the traveling sound waves to realize whether or not the anatomy of the animal can filter out the entering sound waves.

3 Results

These preliminary results are given in terms of pressure map distribution. For the sake of brevity, we focus our attention on pressures over the bony ear complex (tympanoperiotic complex [TPC]). Figure 1 shows the distribution of the pressure due to a traveling 80-kHz frequency-pressure wave. Figure 1a shows a close-up of the left TPC and Figure 1b and c shows the whole body model. The lateral view of the left TPC is shown in Figure 2, where the pressure map is overlaid on the TPC in detail. Figure 2 shows the pressure resulting from a set of frequencies from 80 to 120 kHz, where warm colors indicate high pressure and cold colors indicate low pressure.

These maps show that the various acoustic frequencies illuminate the TPC in different ways. For example, Figure 2a shows a low frequency that is strongly amplified at the ear. Going toward

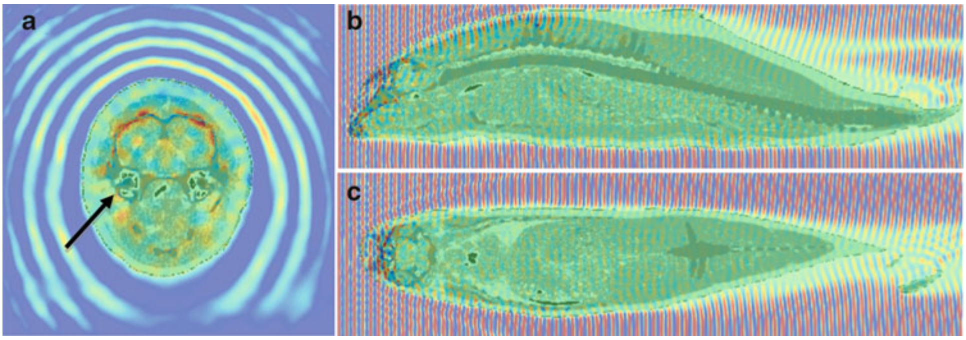

Fig. 1 Sagittal view of the left bony ear complex (**a**) and coronal (**b**), and axial (**c**) views of the whole body of the porpoise. Pressures are shown for an 80-kHz frequency. Arrow indicates position of the left ear

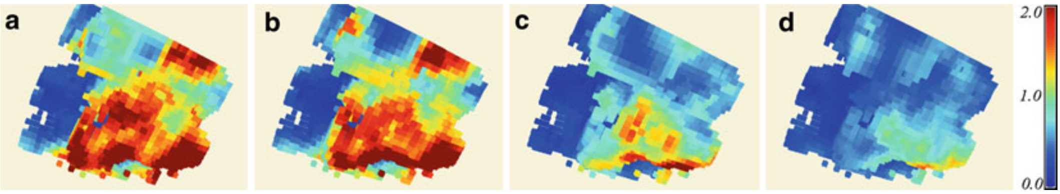

Fig. 2 Pressure results for frequencies of 80 (**a**), 95 (**b**), 110 (**c**), and 120 (**d**) kHz at the left bony ear complex. The pressures are normalized using the external pressure measured at the tip of the porpoise nose. Red indicates twice the pressure at the tip of the rostrum; green shows a pressure that is equal to that at the tip of the rostrum; blue indicates half and lower pressures relative to the tip of the rostrum

120 kHz (upper limit of *Phocoena sinus* hearing; see Gregory 1991), the pressure is focusing, as expected, on a specific spot, presumably responsible for the mechanical functioning of the TPC.

4 Conclusions

This paper addresses *Phocoena sinus* conservation through better understanding of their interaction with the acoustic components of their habitat. An advanced numerical simulation of the interaction of sound with an entire toothed whale is presented here for the first time. The unique FEM model provides a window of understanding into the acoustic functioning. This information may allow us to propose conservation actions to help protect this species. This approach produced the capability to model the acoustic pathways for sound entering the head and the body of these animals.

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