Three-dimensional Computer Modeling of Biosonar Emission in the Common Dolphin

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Abstract: Several delphinid species are known to possess a highly sophisticated and adaptable biosonar system, yet the exact acoustic mechanisms involved in signal generation, emission, and reception remain poorly understood. Recently, a novel computational approach was used to investigate the acoustical mechanisms of dolphin biosonar. Three-dimensional acoustic simulation techniques and a new method for mapping acoustic tissue properties from x-ray computed tomographic data were applied to models of the forehead and lower jaw tissues of the common dolphin, Delphinus delphis. This approach proved highly effective in studying the detailed processes of biosonar emission and reception in this animal. The conclusions of the investigation which concern the emission system of this animal will be presented. These include: 1) the common dolphin's skull plays the predominant role in beam formation; 2) the melon contributes significantly to narrowing of the emitted beams; 3) the melon behaves as a waveguide and a lens in the biosonar signal emission process; 4) the results of both inverse simulation and forward extrapolation programs suggest that the biosonar signal source tissues lie within a small volume of the soft tissues of the right nasal passageway. The results also suggest that the asymmetry of the dolphin's skull and soft tissues is functionally related to the animal's biosonar emission characteristics.

INTRODUCTION

Measurements of the acoustic field of echolocating dolphins have demonstrated that dolphins emit a rapid series of intense clicks in a narrowly focused beam which emanates from the forehead and rostrum. However, despite application of a variety of experimental techniques, the exact mechanisms involved in the generation, emission, and reception of delphinid biosonar signals have remained largely conjectural. Advances in the methodology of bioacoustic simulations have led to powerful combinations of techniques capable of addressing questions that have proven difficult to resolve experimentally. A recent study has successfully combined methods for 3D acoustic simulation and far-field extrapolation with a novel approach to the mapping of acoustic tissue parameters from x-ray computed tomographic (CT) data. These techniques, applied to models of the forehead and lower jaw tissues of the common dolphin, Delphinus delphis, have permitted a detailed investigation of the acoustic principles operating in the biosonar emission and reception processes. The current talk will outline the methods used in this investigation and present the results which concern the biosonar emission system of the common dolphin. Results concerning the location of the biosonar signal source tissues and the roles of the skull, air sacs, and soft tissues (including the melon) in beam formation will be illustrated.

METHOD OF INVESTIGATION

The following method was used to investigate the D. delphis emission system. First, computer models of the tissues of the dolphin’s head were constructed by mapping tissue density and acoustic velocity from x-ray CT data to a simulation grid. Second, 3D finite difference programs were used to simulate acoustic propagation into the tissue models to locate the ‘epicenters’ of the dolphin’s biosonar emissions (analogous to the use of inverse seismologic simulations to pinpoint the epicenters of earthquakes, or to reversing the emission/collection role of an optical lens system). Third, sources were placed at these inverse simulation epicenters or at previously conjectured anatomical source locations, and finite difference programs were again used to propagate the acoustic field of the source and tissue models out to a surface surrounding the tissue region of the grid. Fourth, boundary extrapolation programs were used to compute the emitted acoustic far-field from the pressure and its normal derivative over this surface. Biosonar mechanisms were investigated by visualizing the acoustic energy density within the tissue models and by comparing the fields emitted by various source and tissue models to experimentally measured sonar emissions of live animals. Based on published tissue ultrasound data and established tissue density scanning practices, the 3D tissue modeling technique has a multitude of potential applications and is deserving of further development. Simulation results were quite robust with respect to reasonable variation of the CT-to-density and velocity model mappings.
RESULTS

The importance of the common dolphin's skull in biosonar beam formation is suggested by skull-only simulations which produced significant forward beams solely via reflection off of the upper skull surfaces. Focal maxima were found only in the immediate vicinity of the asymmetrically enlarged right narial depression, and not elsewhere. The fact that these maxima occurred only on the right side of this depression and not on the left suggests that the focal geometry of the skull is functionally related to its asymmetry. Because air sacs cover much of the skull surface in the vicinity of the nasal passages, it is likely that the focal geometry demonstrated here also serves to shape and support the highly reflective flesh-air sac boundaries.

Much speculation has surrounded the acoustic role of the fatty melon tissues of the delphinid forehead. In the common dolphin, skull asymmetry parallels the asymmetry of the refractive soft tissues of the forehead and nasal passages. The current simulations show that the melon and other soft tissues of the *D. delphis* forehead significantly narrow the main forward beam. The melon's effect in narrowing the horizontal beam appears greater than its effect on the vertical beam. In addition, the inverse skull and soft tissue simulations demonstrate a pronounced tendency towards collimation or channeling of acoustic energy within the posterior throat of the melon. The posterior melon thus appears effective as a 'leaky' waveguide, while the larger forward lobe of the melon has been confirmed to operate as a lens in the biosonar emission process. The tissue modeling techniques have also permitted illustration of the density, velocity, and impedance structure of the *D. delphis* melon. Several fundamental acoustic mechanisms operating in the forehead tissues may be surmised directly from the resulting diagrams.

Dramatic evidence for the location of the biosonar signal source tissues in the common dolphin was obtained. A clustering of inverse simulation foci in the complete model has implicated a small (roughly 1 cc) volume of tissue centered approximately 0.7 cm below the center of the right MLDB complex as the most plausible 'epicenter' of the dolphin's biosonar clicks. This result best supports the conjecture that the right MLDB complex is the source tissue of the pulsed biosonar signals of odontocetes. Inverse simulation foci were notably absent from other previously proposed source locations (including the larynx, the right nasal plug node, and the left MLDB). The fact that foci in the complete model were found only on the right side of the nasal passageway is consistent with the separation of the sources of clicks and whistles into the right and left sides, respectively, of the delphinid nasal passages. The nonviability of the larynx and right nasal plug as source locations for biosonar clicks was further illustrated by forward extrapolations of the far-field patterns produced by point sources placed at the tip of the larynx and within the node of the right nasal plug.

In summary, a powerful combination of numerical techniques has enabled demonstration of a number of the acoustic principles operating in biosonar beam formation by the forehead tissues of the common dolphin. It is expected that similar if not identical mechanisms operate in all delphinids exhibiting intermediate-to-moderate soft tissue asymmetry. It is also reasonable to suggest that similar mechanisms may operate in all odontocetes that possess forehead structures resembling those of the common dolphin.

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