

Building a Virtual Model of a Baleen Whale

Dr. Ted W. Cranford, Chief Scientist
Quantitative Morphology Consulting, Inc.
2674 Russmar Dr.
San Diego, CA 92123-3422
phone: (619) 226-7944 fax: (619) 226-7944 email: Ted.W.Cranford@gmail.com

Capt. Jim Christmann
Monterey Canyon Research Vessels, Inc.
114 Mason Street
Santa Cruz CA 95060-4713
phone: (831) 423-4864 fax: (831) 423-4864 email: jaxmann@shanarae.com

Award Number: N00014-10-1-0736
<http://www.shanarae.com>

LONG-TERM GOALS

This long term goal of this research is to eventually CT scan an adult baleen whale. The research effort will be subdivided into three phases. The current activity only covers Phase 1, the design and testing phase. No marine mammal specimens are needed in this initial design and testing phase. Going forward with Phases 2 and 3 will be dependant upon the success of Phase 1.

OBJECTIVES

Phase 1 will accomplish the following objectives:

1. Investigate, design, test, and purchase an insulated tow bag that will, in later phases, eventually be used to contain a whale carcass and transport it to a haul-out marina where it can be hoisted into a steel cradle.
2. Design, build, and test a recirculating sea water chilling system. This unit would be palletized and plumbed so that sea water can be recirculated into the insulated bag while the specimen is towed into the marina. This will help stave off decomposition.
3. Test towing and handling procedures with insulated bag and recirculating chilled sea water system. Measure the rate at which the sea water can be chilled while towing a bag full of sea water.
4. Design and build a steel cradle that used to hold specimen while hoisting it from the water and during transport from the marina to freezer unit.
5. Video documentation will be ongoing throughout the life of the project. If we succeed in Phase 1 of this project, we will be on track to revolutionize our understanding of the largest animals on Earth. As a consequence, this project will have demonstrated an innovative process that may serve the public interest and as a pattern for future studies.

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 30 SEP 2011		2. REPORT TYPE		3. DATES COVERED 00-00-2011 to 00-00-2011	
4. TITLE AND SUBTITLE Building a Virtual Model of a Baleen Whale				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Quantitative Morphology Consulting, Inc.,2674 Russmar Dr,San Diego,CA,92123-3422				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 7	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

APPROACH

Short of experimentally exposing live animals, which is always expensive and often impossible, the most promising technique for discovering acoustic pathways and assessing potential effects from any particular sound, involves finite element modeling (FEM). The FEM method has been applied successfully to engineering problems over the past half century and is now in widespread use.

Our team has pioneered a suite of techniques that combine anatomic geometry obtained from CT scanners (Cranford, 1988; Cranford, 1999; Cranford et al., 1996), measurements of tissue elasticity (Soldevilla et al., 2005), and custom FEM software (Krysl et al., 2006), which produces a versatile computational environment for acoustic simulations (Krysl et al., 2008). These techniques can be used to assess acoustic exposure across a broad taxonomic spectrum.

The intellectual merit of these methods has been demonstrated by the recently published discovery of a new pathway for sound entering the head of a beaked whale (Cranford et al., 2008a) and function of the hearing apparatus in toothed whales (Cranford et al., 2010). These results challenges the long accepted paradigm of toothed whale hearing (Norris, 1968). In addition, anatomic similarities with all living toothed whales suggest that this new pathway may also be the original pathway used by the ancient whales (archaeocetes) in the Eocene. This discovery was catalyzed by the disparate views and collective efforts of experts in different disciplines, the essence of our approach.

These computer-enabled investigative methods have already transformed our capacity to generate original knowledge and understand the bioacoustics of marine mammals (Cranford, 2000; Cranford and Amundin, 2003; Cranford et al., 2008a; Cranford et al., 2008b). The resulting simulations allow us to emulate, for example, the formation of an acoustic transmission beam or measure the amplitude differences and time delay for sound reaching each ear complex. These are just a few examples of the predictions and understanding we can glean from basic simulations.

The current project proposes to eventually CT scan an adult baleen whale. This goal may, at first, seem unattainable, but it is feasible. This daunting goal is attainable because over the past ten years, one of us (Cranford) has developed and tested a technique to scan large cetacean specimens (Cranford 1999). Once obtained the CT scan of an adult mysticete opens a broad spectrum of research offshoots that hold the potential to revolutionize our understanding of the anatomy and physiology of the largest animals on Earth. This project is the first phase of an effort that will eventually simulate mysticete hearing, a primary topic of interest to the Office of Naval Research.

The project will be subdivided into three phases. This report covers Phase 1, the design and testing phase. No marine mammal specimens were needed in this initial design and testing phase (Phase 1).

We plan to tow the whale carcass tail-first, and winch it slowly backwards into a trailing open bag; or the bag can be winched forward over the carcass. In either case, the mechanical winch achieves the goal of a bagged, refrigerated carcass under slow, controlled tow. The result is a carcass that is isolated in a volume of seawater inside the bag.

The seawater will be cooled and recirculated during the entire tow into the marina. The pallet-mounted portable chiller is a diesel-driven refrigeration system that will pump recirculating enhanced brine through the bag containing the carcass from the deck of the towing vessel. It will achieve a freezing point somewhat lowered from that of seawater, through a hose inserted into the specimen's

mouth, and recurved back toward the esophagus. The coldest water will flow forward and out into the bag, with a return suction line sending water back to the chiller from out in the bag.

The bag will isolate and insulate a finite volume of seawater that recirculates through the on-deck chiller. This should allow the hearing apparatus in the anterior part of the head to be cooled by progressively lower temperature water, for as long as the towing takes place. The lowest temperature limit is the freezing point of the enhanced brine, but only after substantial cooling and equilibrium of some or much of the specimen's anterior anatomy has been achieved. This will certainly take many hours, but this seems the best way to introduce cooling as quickly as possible; and if a tow is to take many hours at very low speed then the time would be used wisely by introducing cooling early.

The bagged, cooled, and towed carcass will then be brought to the nearest haulout yard, where an appropriately-sized prefabricated steel cradle will be lowered into the water. The bagged carcass will be winched tail-first into the steel cradle. The cradle is capped at both ends, with some volume of harbor water supporting (partially floating) the specimen's entire bulk in water. The cradle, having been designed specifically for this purpose, is then raised from the water, wheeled to a waiting, chartered flatbed truck trailer, and lowered onto same, just as these facilities do every day with 20 and 30 ton sailboats and commercial vessels. The cradle is secured on the flatbed, the on-deck chiller system is transferred from the boat deck to the truck bed, after which the circulating refrigeration hoses are re-connected to the specimen, and the cooling process resumes.

If all goes well, then this specimen could be the most carefully handled and preserved ever seen by investigators, with none of the crushing associated with beached or shipboard specimens, and as little decomposition as circumstances and cooling physics will allow. We will be in close contact with Monterey Bay charter vessels that are likeliest to witness an Orca kill on an appropriately-sized subadult Gray Whale. The tow vessel will be adequately prepared and equipped as the migration approaches, so that all these factors might coincide to allow this process to unfold in an auspicious manner.

WORK COMPLETED

Project Schedule and Milestones

Phase 1 – Christmann & Cranford (current effort)

- ✓ Investigate, design, and purchase insulated tow bag (complete by Jan. 2011)
- ✓ Purchase, refurbish, and modify surplus net reel to hold tow bag for ship-board deployment
- ✓ Design steel cradle used to hold specimen during transport
- Build, and test steel cradle used to hold specimen during transport
- Chiller construction – palletized recirculating sea water system
- ✓ Test towing procedures with insulated bag
- ✓ Video documentation of operations (ongoing throughout the funding period)

The tasks marked with a check have been completed.

Phase 2 – Cranford & Christmann (Future Proposal 2011)

- Boat agreements and negotiations
- Locating specimen (probably airplane)
- Tow it in while chilling
- Hoist out and put in truck
- Transport to stand alone freezer
- Cut into sections if necessary
- Ship sections to Hill AFB for scanning
- Back to freezer and then ship to Smithsonian Institution for dissection and storage of skeleton

Phase 3 – Krysl & Cranford (Future Proposal – 2012)

- Begin image processing and model preparation effort

We have manufactured a large insulated, canvas-reinforced bag that can be used to capture and tow a subadult Gray Whale (*Eschrichtius robustus*) carcass to a marina for extraction. We also purchased a surplus gill net reel that has been refurbished and modified to hold the rolled up towing bag so that it can be easily loaded and unloaded from the deck of the work boat. The net reel also facilitates easy deployment of the bag to capture the whale carcass. All operations will be launched from the deck of the 50-foot research vessel Shana Rae, based in Santa Cruz, CA (see <http://www.shanarae.com>). The hydraulics controls on the Shana Rae have been relocated and modified so that they can be used from a position where deck operations are visible over the loaded net reel.

The capture and towing process have been hydrodynamically demonstrated twice. First, we used a scale model of the bag (approximately 1/20 scale) with an albacore carcass to simulate the Gray Whale. Then we conducted an actual tow of the full size bag in the ocean. These tests showed a nearly flawless opening and then a level, controlled tow of the bag. This occurred both on the scale model and the first attempt at deploying the full size bag in the ocean. When the towing bag came off the reel and went into the water, it towed very smoothly and operated as planned. This exercise provided a successful demonstration of methodological viability. The process was captured on a digital video recorder.

We have worked with Sanctuary Stainless, a metal fabricator (in Moss Landing, CA), to design the specialized steel cradle and the palletized chiller system. This fabricator is a ex-commercial fisherman with decades of experience in refrigeration. The cost estimates for the steel cradle and portable chiller represent substantial resource outlays. We are ready to proceed with construction of both items as soon as resources become available.

IMPACT/APPLICATIONS

Navy sonar training operations have been hampered by concerns and lawsuits over the effects that high intensity sound exposure might have on marine organisms, especially the mammals.

There is worldwide interest in the potential effects of anthropogenic sound on mysticete (baleen) whales. Most of the research on the effects of sound has been conducted on a few small marine mammal species that can be housed in research labs and aquaria. But little is known about the anatomy and physiology of bioacoustics in large mysticetes, except recording their sounds. Low-frequency long-wavelength sounds, like those produced during naval and other industrial operations, are likely to produce the most significant interactions with the bodies of these largest of marine mammals.

One viable method to assess exposure employs a computer modeling (FEM) environment to interrogate animal systems, increasing our understanding of how those systems work, simulating the response of those systems to insult from high-intensity sounds, and assessing possible mitigation strategies prior to implementation. Producing this modeling environment is economical when compared to live animal work and provides a broad scope for investigation that cannot be matched or risked with live animals. Finally, the modeling environment allows investigators the flexibility to pivot quickly and nimbly to address inquiries of new or potential problems as they arise.

There is another realm of understanding that can be tapped by using FEM methods, but it might not be immediately obvious. The FEM tools allow us to conduct virtual experiments, a powerful but subtle capability. Consider the value of teasing apart the contributions of anatomic components that may serve in acoustic filtering or selective amplification along the sound reception pathways. We have plans to use these FEM tools to “test” the ramifications of selected changes to Navy sonar signal characteristics and to evaluate various mitigation strategies or simulate the impact of explosions. The ability to conduct virtual experiments may prove to be the most powerful facet of the development of these FEM tools.

The success of this project will mark a sudden and conspicuous transformation in our understanding of the anatomy of mysticetes. To date, our knowledge of the anatomy of baleen whales has been largely based upon reports of centuries old dissections, using hand tools and draft animals with block and tackle, and from the whaling industry. It is a pity that the last published reference on systemic anatomy in baleen whales was by von Schulte (1916), for a fetal fin whale. Clearly, the methodology developed for this project will greatly advance our understanding of mysticete acoustic functional morphology.

There are two major advancements that accrue from capturing in situ anatomy in an adult mysticete as a means for understanding acoustic function: the complex geometry of anatomic structure and an advantages of changing the perspective to that anatomy. In other words, the sizes, shapes and material composition of organs and tissue interfaces will largely determine the interactions with acoustic stimuli, so it is important to capture this information. In addition, the immense size of these animals makes it very difficult to comprehend the perspective on their anatomic structure. This is particularly true if we rely solely upon traditional dissection methods because then structures are much larger than the observer and attempts to separate the slumping anatomic components will all but destroy the indispensable anatomic geometry. These factors are currently unknown for any adult mysticete.

Modeling has several advantages. Models are flexible with respect to species and the variety of acoustic stimuli that can be tested. Once developed, models are inexpensive to reuse in light of new information or to address new questions. The models we propose are constructed at the organismal level. This allows us to investigate interactions on the whole organism or to zoom in on structures or suites of structures to address questions of sound propagation and transmission across interfaces, or the

distribution of acoustic pressure and shear stresses, or dissipated energy and heating effects, or identify any excessive strains or displacements due to resonance, or the potential for cavitation, and other potential mechanical effects of vibroacoustic impacts.

RELATED PROJECTS

This project is unique. There are no related projects.

REFERENCES

Cranford, T. W. (1988). The anatomy of acoustic structures in the spinner dolphin forehead as shown by X-ray computed tomography and computer graphics. In *Animal sonar: processes and performance*, eds. P. E. Nachtigall and P. W. B. Moore), pp. 67-77. New York: Plenum Publishing Corporation.

Cranford, T. W. (1999). The sperm whale's nose: Sexual selection on a grand scale? *Mar. Mam. Sci.* **15**, 1133-1157.

Cranford, T. W. (2000). In search of impulse sound sources in odontocetes. In *Hearing by whales and dolphins*, eds. W. W. L. Au A. N. Popper and R. R. Fay), pp. 109-156. New York: Springer-Verlag.

Cranford, T. W., Amundin, M. and Norris, K. S. (1996). Functional morphology and homology in the odontocete nasal complex: Implications for sound generation. *J. Morphol.* **228**, 223-285.

Cranford, T. W. and Amundin, M. E. (2003). Biosonar pulse production in odontocetes: The state of our knowledge. In *Echolocation in bats and dolphins*, eds. J. A. Thomas C. F. Moss and M. Vater), pp. 27-35. Chicago: The University of Chicago Press.

Cranford, T. W., Krysl, P. and Amundin, M. (2010). A new acoustic portal into the odontocete ear and vibrational analysis of the tympanoperiotic complex. In *PLoS ONE*, vol. 5, pp. 1-29: Public Library of Science.

Cranford, T. W., Krysl, P. and Hildebrand, J. A. (2008a). Acoustic pathways revealed: Simulated sound transmission and reception in Cuvier's beaked whale (*Ziphius cavirostris*). *Bioinsp. Biomim.* **3**, 1-10.

Cranford, T. W., McKenna, M. F., Soldevilla, M. S., Wiggins, S. M., Shadwick, R. E., Goldbogen, J., Krysl, P., St. Leger, J. A. and Hildebrand, J. A. (2008b). Anatomic geometry of sound transmission and reception in Cuvier's beaked whale (*Ziphius cavirostris*). *Anat. Rec.* **291**, 353-378.

Krysl, P., Cranford, T. W. and Hildebrand, J. A. (2008). Lagrangian finite element treatment of transient vibration/acoustics of biosolids immersed in fluids. *Int. J. Numer. Meth. Engng.* **74**, 754-775.

Krysl, P., Cranford, T. W., Wiggins, S. M. and Hildebrand, J. A. (2006). Simulating the effect of high-intensity sound on cetaceans: Modeling approach and a case study for Cuvier's beaked whale (*Ziphius cavirostris*). *J. Acoust. Soc. Am.* **120**, 2328-2339.

Norris, K. S. (1968). The evolution of acoustic mechanisms in odontocete cetaceans. In *Evolution and environment*, (ed. E. T. Drake), pp. 297-324. New Haven: Yale University Press.

Soldevilla, M. S., McKenna, M. F., Wiggins, S. M., Shadwick, R. E., Cranford, T. W. and Hildebrand, J. A. (2005). Cuvier's beaked whale (*Ziphius cavirostris*) head tissues: physical properties and CT imaging. *J. Exp. Biol.* **208**, 2319-2332.

von Schulte, H. (1916). Anatomy of a fetus of *Balaenoptera borealis*. *Mem. Am. Mus. Nat. Hist.* **1**, 389-502.