Evolution of echolocation in toothed whales

Rachel Racicot
WM Keck Science Department, Claremont McKenna, Pitzer, and Scripps Colleges
Why is evolution of underwater echolocation important?

A) Conservation applications
   – we need to know the anatomy of biosonar apparatus in marine animals to mitigate the impacts of human-produced sonar/sound

B) Engineering & robotics applications
   – how & why one group of mammals evolved & uses underwater echolocation have direct human applications

C) Understanding evolutionary trends
   – are smaller, fully aquatic members of certain lineages destined to echolocate?

D) All of the above
   – …and more!
What is the echolocation apparatus in toothed whales?
Cranford et al. 1996

Specialized aquatic sensory structures

Blowhole

Air sacs + phonic lips

Brain processes

Ear sends signals to brain

Fat pads in jaw; high-density ear bones

Cranford et al. 1996
Whales have undergone one of the most dramatic transitions in mammalian history
Toothed whales

Baleen whales
How do we measure hearing in whales?
How do we assess hearing in living whales?
Spiral “types” associated with hearing

Odontoceti

Type I
peak spectra
above 100 kHz

Type II
peak spectra
below 80 kHz

Mysticti

Ketten 1992
If estimated for species with unknown hearing ranges, what about fossils?

Fossils can then tell us when and possibly why specialized hearing evolved in certain lineages.
X-Ray microCT

Non-destructive, quick (< 1 hour), µm-scale resolution (maps X-ray attenuation)
Porpoise fossil *Salumiphocaena stocktoni*

Racicot et al. 2016 *BJLS*
Salumiphocaena stocktoni

Base (higher frequency sound sensitivity)

Racicot et al. 2016 BJLS
Apex (lower frequency sound sensitivity)
Measurements correlate with hearing sensitivity

Cochlear spiral length

Racicot et al. 2016 BJLS
Proxies for specialized hearing frequencies

9 measurements for each taxon plugged into PCA

Racicot et al. 2016 BJLS
Oligocene: Key time for evolution of echolocation

Geisler et al. 2013
Oligocene: Key time for evolution of echolocation

Xenorophidae

Geisler et al. 2013
Oligocene: Key time for evolution of echolocation

Simocetidae

Geisler et al. 2013
Simocetus rayi

Unusual skull shape may represent specialized feeding mode

Evidence for echolocation on skull surface (Fordyce 2002)

Illustration by Carl Buell
Xenorophid inner ear labyrinths indicate echolocation

_Echovenator sandersi_ (Racicot et al. _in review_; see also Churchill et al. 2016 & Park et al. 2016)

Geisler et al. 2013
Echolocation evolved in one early odontocete lineage, but what about those more closely related to Crown Odontoceti?
Echolocation evolved in one early odontocete lineage, but what about those more closely related to Crown Odontoceti?

Geisler et al. 2013
Echolocation evolved in one early odontocete lineage, but what about those more closely related to Crown Odontoceti?
Olympicetus cf. closely resembles Olympicetus avitus (Vélez-Juarbe 2017)
Heavily pruned, strict consensus tree including *Olympicetus* cf. (CCNHHM 1000)
Heavily pruned, strict consensus tree including *Olympicetus* cf. (CCNHM 1000)
Olympicetus sp. ear bone

Whole petrosal & close-up of bony labyrinth μCT scanned at Department of Earth and Environmental Sciences, Vanderbilt University

Resolution: 17.2 μm

Digital endocast constructed using VGStudioMax 2.2; measurements taken using Avizo and VGStudioMax
Olympicetus sp.
Olympicetus sp.
Olympicetus sp. anatomy, measurements

9 cochlear measurements *sensu* Mourlam & Orliac 2017
Olympicetus sp. anatomy, measurements

Secondary bony lamina length

9 cochlear measurements sensu Mourlam & Orliac 2017
*Olympicetus* sp. anatomy, measurements

9 cochlear measurements *sensu* Mourlam & Orliac 2017
Olympicetus sp. anatomy, measurements

9 cochlear measurements sensu Mourlam & Orliac 2017
Olympicetus sp. anatomy, measurements

Cochlear length (full length along laminar gap)

9 cochlear measurements *sensu* Mourlam & Orliac 2017
Olympicetus sp. anatomy, measurements

Cochlear width

9 cochlear measurements sensu Mourlam & Orliac 2017
Olympicetus sp. anatomy, measurements

9 cochlear measurements sensu Mourlam & Orliac 2017
Olympicetus sp. anatomy, measurements

9 cochlear measurements sensu Mourlam & Orliac 2017
Olympicetus sp. anatomy, measurements

9 cochlear measurements sensu Mourlam & Orliac 2017
Olympicetus sp. anatomy, measurements

Cochlear height

9 cochlear measurements sensu Mourlam & Orliac 2017
Olympicetus sp. anatomy, measurements

9 cochlear measurements sensu Mourlam & Orliac 2017

At first quarter turn:
Spiral ganglion canal width
What do you think I found?

A) *Olympicetus* sp. had specialized high frequency hearing, & consequently echolocated

B) *Olympicetus* sp. did not have high frequency hearing, & consequently may not have echolocated
Discussion/Conclusions

Transitional (between archaeocete and modern) type of hearing in *Olympicetus* sp., other early dolphins? – which have a parallel style of “telescoping” of the skull and different skull structure to xenorophids
Discussion/Conclusions

Transitional (between archaeocete and modern) type of hearing in *Olympicetus* sp., other early dolphins? – which have a parallel style of “telescoping” of the skull and different skull structure to xenorophids

Possible multiple origins of echolocation in toothed whales!
Where do we go from here?
Multiple origins of echolocation in dolphins?

Fine examination of lineages more closely related to extant species should illuminate origins in the lineage we see today.

More work to be done!

What does it mean?

Different ways to converge on biosonar

– conservation

– robotics/engineering applications

– large-scale evolutionary patterns in dolphins & early relatives
Morphological characters

Neuroanatomy – interpret sensory input

Nerve canals

Pneumaticity

Inner ear – auditory and balance sensory systems

Thank you

Collections: AMNH, NMNH, NMNS, SDNHM, LACM, MCZ, UCMP

Funding:
WM Keck Science Department
Vanderbilt University
American Cetacean Society
Society for Marine Mammalogy
Natural History Museum of Los Angeles County
National Science Foundation
NSF–EAPSI
Japan Society for the Promotion of Science
Paleontological Society AJ Boucot Research Grant
Yale Department of Geology & Geophysics
Yale Institute for Biospheric Studies Dissertation Enhancement Grant
AMNH Lerner Grey Fund For Marine Research