**Electronic Supplementary Material for: Convergent evolution in toothed whale cochleae**

**Specimen List**

Table S1. Specimens used in this study. Institutional abbreviations: AMNH, American Museum of Natural History, New York, USA; IRNSBV, Belgian Royal Institute of Natural Sciences, Brussels, Belgium; NMB, Naturhistorisches Museum Basel, Basel, Switzerland; NHMUK, Natural History Museum, London, England; NMVC, Museums Victoria, Melbourne, Australia.

|  |  |  |
| --- | --- | --- |
| Taxon | Specimen number | Resolution (μm) |
| *Cephalorhynchus commersonii* | NHMUK1952.6.20.4 | 32.08 |
| *Cephalorhynchus heavisidii* | NHMUK1948.7.27.1 | 32.08 |
| *Delphinus delphis* | NMB6679 | 40 |
| *Feresa attenuata* | NHMUK1874.11.25.1 | 47.52 |
| *Globicephala melas* | NHMUK1947.12.31.4 | 32.11 |
| *Grampus griseus* | NHMUK1920.12.16.1 | 25.72 |
| *Lagenodelphis hosei* | NHMUK1895.5.9.1 | 38.75 |
| *Lagenorhynchus acutus* | NHMUK1928.19 | 32.27 |
| *Lagenorhynchus albirostris* | NHMUK1848.7.12.12 | 32.08 |
| *Lagenorhynchus australis* | NHMUK1944.11.30.1 | 32.27 |
| *Lagenorhynchus cruciger* | NHMUK1960.8.24.1 | 32.27 |
| *Lagenorhynchus obliquidens* | NHMUK1966.10.25.1 | 39.75 |
| *Lagenorhynchus obscurus* | NHMUK1841.1733 | 39.75 |
| *Orcaella brevirostris* | NHMUK1883.11.20.2 | 32.11 |
| *Orcinus orca* | NHMUK1927.28 | 39.84 |
| *Peponocephala electra* | NHMUK1992.100 | 32.08 |
| *Pseudorca crassidens* | NHMUK1992.248 | 39.84 |
| *Sotalia fluviatilis* | NHMUK1856.8.2.2 | 43.75 |
| *Sotalia guianensis* | IRSNBV20137 | 30.47 |
| *Sousa chinensis* | NHMUK1914.1.14.1 | 32.27 |
| *Stenella attenuata* | NHMUK1990.98 | 37.66 |
| *Stenella coeruleoalba* | NHMUK1940.3.2.1 | 37.66 |
| *Stenella longirostris* | NHMUK1990.104 | 32.27 |
| *Steno bredanensis* | NMVC36961 | 32.97 |
| *Tursiops aduncus* | NHMUK1882.1.2.3 | 39.75 |
| *Tursiops truncatus* | NHMUK1866.8.7.1 | 32.27 |
| *Inia geoffrensis* | NMB7167 | 30 |
| *Kogia breviceps* | NMVC24976 | 33.07 |
| *Kogia sima* | NHMUK1952.8.28.1 | 32.27 |
| *Lipotes vexillifer* | AMNH57333 | 30.7 |
| *Delphinapterus leucas* | NMBCIII1086 | 40 |
| *Monodon monoceros* | AMNH73315 | 40.69 |
| *Neophocaena phocaenoides* | NHMUK1903.9.12.3 | 32.27 |
| *Phocoena dioptrica* | NHMUK1939.9.30.1 | 38.75 |
| *Phocoena phocoena* | NMVC27654 | 33.08 |
| *Phocoena spinipinnis* | IRSNBV21219 | 27.35 |
| *Phocoenoides dalli* | NHMUK1965.1.19.2 | 43.75 |
| *Physeter macrocephalus* | NHMUK893 | 42.14 |
| *Platanista gangetica* | NMVC27417.2 | 41.5 |
| *Pontoporia blainvillei* | MNHN1934.375 | 38 |
| *Berardius arnuxii* | NHMUK1982.315 | 49.67 |
| *Hyperoodon ampullatus* | NHMUK1862.12.2.2 | 41.06 |
| *Mesoplodon bidens* | IRSNB16232 | 35 |
| *Mesoplodon grayi* | NMVC31378 | 44.02 |
| *Mesoplodon hectori* | NHMUK1876.2.16.3 | 30.11 |
| *Mesoplodon mirus* | NHMUK1920.5.20.1 | 47.52 |
| *Tasmacetus shepherdi* | NMVC37967.6 | 58.28 |
| *Ziphius cavirostris* | NHMUK1915.7.20.1 | 33.57 |

**Landmark/curve Definitions**

*Fenestra vestibuli*

Curves 0 – 3: 4 curves (1 per quarter): starts at midline of vestibular curve, travels anticlockwise (in vestibular view), at level of the point where the lateral semi-circular canal meets the fenestra vestibuli, finishes on same point

*Cochlear canal*

Curves 4 – 11: 8 curves on medial-most outline of scala vestibuli: starts where vestibular curve meets cochlear canal, finishes on apex

Curves 12 – 19: 8 curves on ventral-most outline of scala vestibuli: starts where vestibular curve meets cochlear canal, finishes on apex

Curves 20 – 30: 11 curves lateral most outline of scala vestibuli (starting at dorsal-most point of scala vestibuli), finishes on apex

Curves 31 – 39: 9 curves dorsal-most outline of scala tympani (starting just anterior to where cochlear aqueduct joins cochlear canal), finishes on apex

*Vestibular aqueduct*

Curve 40: 1 curve along its length ending at endolymphatic sac: runs along anterior surface



Figure S1. Cochlea of *Cephalorhynchus commersoniii* (NHMUK1952.6.20.4.2) in: (A) vestibular; (B) anterior; (C) dorsal; and (D) lateral views, showing placement of landmarks for this study.

**Chi-squared analyses results**

Table S2. Results of *χ*2 analysis. *Χ*2: chi-squared value; df: degrees of freedom; bc: Bonferroni corrected *p*-value. Habitat1: all “riverine/nearshore” taxa are classed as “riverine” and “nearshore/oceanic” taxa are classed as “nearshore”; Habitat2: all “riverine/nearshore” taxa are classed as “nearshore” and “nearshore/oceanic” taxa are classed as “oceanic”; Feeding1: all “raptorial/suction” taxa are classed as “raptorial”; Feeding2: all “raptorial/suction” taxa are classed as “suction”. Significant ecological categories in bold.

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Regime A** |  |  |  | **Regime B** |  |  |  | **Regime C** |  |  |  |
|  | **x2** | **df** | ***p*-value** | **bc *p*-value** | **x2** | **df** | ***p*-value** | **bc *p*-value** | **x2** | **df** | ***p*-value** | **bc *p*-value** |
| Diet | 3.224 | 2 | 0.200 | 1 | 6.860 | 2 | 0.032 | 0.583 | 4.466 | 2 | 0.107 | 1 |
| Habitat 1 | 16.39 | 2 | 0.000 | **0.005** | 4.174 | 2 | 0.124 | 1 | 1.699 | 2 | 0.428 | 1 |
| Habitat 2 | 3.725 | 2 | 0.155 | 1 | 0.949 | 2 | 0.622 | 1 | 1.455 | 2 | 0.483 | 1 |
| Feeding 1 | 6.350 | 1 | 0.012 | 0.211 | 0.568 | 1 | 0.451 | 1 | 1.517 | 1 | 0.218 | 1 |
| Feeding 2 | 5.749 | 1 | 0.017 | 0.297 | 0.479 | 1 | 0.489 | 1 | 1.335 | 1 | 0.248 | 1 |
| Dive type | 8.908 | 2 | <0.001 | **<0.001** | 2.268 | 2 | 0.028 | 0.517 | 3.478 | 2 | 0.051 | 0.918 |

**3 PC & 4 PC Analyses Results**

*SURFACE analyses*

Table S3. Results of the SURFACE analysis using 3 PCs. Parameters were found by the evolutionary models fitted to the evolution of cochlear shape in toothed whales described by PC1, PC2 and PC3. Abbreviations: α, rate of adaptation to optima; *t*1/2,; σ2, rate of stochastic evolution; θ, optimum trait value for each regime.

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter | Value |  |  |
| AICc | -547.6001 |  |  |
| Phenotypic regimes | 6 |  |  |
| Pheno reg shifts | 9 |  |  |
| Conv pheno reg | 3 |  |  |
| Conv reg shifts | 6 |  |  |
| Conv fraction | 0.66 |  |  |
|   | PC1 | PC2 | PC3 |
| α | 0.3055731 | 3.5860466 | 0.2034437 |
| *t*1/2 | 2.2683512 | 0.1932901 | 3.4070705 |
| σ2 | 0.000394199 | 0.00459924 | 0.000389555 |
| θa | 0.06475327 | 0.05540134 | 0.054914713 |
| θb | 0.05525293 | -0.0979297 | 0.424337912 |
| θc | 0.10949494 | 0.17117225 | 0.105221289 |
| θd | -0.12552789 | -0.0105983 | 0.016383934 |
| θf | 0.01960091 | -0.0127686 | -0.01536403 |
| θg | -0.07812261 | 0.13443546 | -0.00662119 |

Table S4. Results of the SURFACE analysis using 4 PCs. Parameters were found by the evolutionary models fitted to the evolution of cochlear shape in toothed whales described by PC1, PC2, PC3 and PC4. Abbreviations: α, rate of adaptation to optima; *t*1/2, expected time to evolve halfway to an optimum; σ2, rate of stochastic evolution; θ, optimum trait value for each regime.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Parameter | Value |  |  |  |
| AICc | -723.6117 |  |  |  |
| Phenotypic regimes | 7 |  |  |  |
| Pheno reg shifts | 9 |  |  |  |
| Conv pheno reg | 2 |  |  |  |
| Conv reg shifts | 4 |  |  |  |
| Conv fraction | 0.44 |  |  |  |
|   | PC1 | PC2 | PC3 | PC4 |
| α | 0.2126589 | 0.2834478 | 0.1456725 | 0.1111551 |
| *t*1/2 | 3.259431 | 2.445414 | 4.758257 | 6.235857 |
| σ2 | 0.00028452 | 0.00045942 | 0.00030189 | 0.000159964 |
| θa | -0.12532507 | -0.01065699 | 0.016172771 | -0.017275535 |
| θb | 0.06922345 | -0.17092699 | 0.556174253 | 0.630543914 |
| θc | 0.12299196 | 0.24896805 | 0.113935723 | -0.047773283 |
| θd | -0.07552558 | 0.14403766 | -0.008966596 | 0.069964052 |
| θe | 0.0868295 | -0.06262475 | -0.077356961 | -0.364601342 |
| θg | 0.06390308 | 0.0377028 | 0.054711786 | -0.045510447 |
| θh | 0.01874895 | -0.01094644 | -0.015387493 | 0.002121349 |

*C-metric analyses*

Table S5. C1 - C4 convergence measures and *p*-values using 3 PCs. *P*-values were derived from 1000 simulations to test the hypothesis that the observed values are greater than random simulations based on Brownian motion. Significant values in bold.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Regime A | C1 | C2 | C3 | C4 |
| C-value | 0.68877399 | 0.12592615 | 0.39373833 | 0.02373326 |
| P-value | **0** | **0** | **0** | **0** |
|  |  |  |  |  |
| Regime B | C1 | C2 | C3 | C4 |
| C-value | 0.849605 | 0.2225559 | 0.5308192 | 0.4826925 |
| P-value | **0** | **0** | **0** | **0** |
|  |  |  |  |  |
| Regime C | C1 | C2 | C3 | C4 |
| C-value | 0.256274777 | 0.031864892 | 0.056861626 | 0.006005566 |
| P-value | 0.07792208 | **0.04195804** | 0.31368631 | 0.30669331 |

Table S6. C1 - C4 convergence measures and *p*-values using 4 PCs. *P*-values were derived from 1000 simulations to test the hypothesis that the observed values are greater than random simulations based on Brownian motion. Significant values in bold.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Regime D | C1 | C2 | C3 | C4 |
| C-value | N/A | N/A | N/A | N/A |
| P-value | N/A | N/A | N/A | N/A |
|  |  |  |  |  |
| Regime E | C1 | C2 | C3 | C4 |
| C-value | 0.7049156 | 0.2275502 | 0.4730401 | 0.4382331 |
| P-value | **0.000999001** | **0.000000000** | **0.000000000** | **0.000000000** |

*Wheatsheaf analyses*

Table S7. Results of the Wheatsheaf index analysis using 3 PCs. WI: Wheatsheaf index.

|  |  |  |  |
| --- | --- | --- | --- |
| Conv reg | WI value | P-value | 95% CI |
| Regime A | 1.022464 | 0.747 | 0.9526044 - 1.089544 |
| Regime B | 2.194074 | 0.34 | 2.092535 - ∞ |
| Regime C | 1.472754 | 0.679 | 1.404596 - 2.749955 |

Table S8. Results of the Wheatsheaf index analysis using 4 PCs. WI: Wheatsheaf index.

|  |  |  |  |
| --- | --- | --- | --- |
| Conv reg | WI value | P-value | 95% CI |
| Regime D | 2.420819 | 0.292 | 2.324896 - ∞ |
| Regime E | 0.951743 | 0.14 | 0.9319229 - 0.9725553 |



Figure S2. Cladogram showing the phylogenetic relationships of the taxa in this study.