The relationship between salt gland depression size and proportion of fish in the diet of penguins

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Introduction

What are salt glands?

- An adaptation that can allow marine organisms to ingest seawater and prey that is as salty as seawater
- Function to excrete sodium chloride in the form of highly saline water droplets
- Conspicuous glands found in cartilaginous fish, marine reptiles, and marine birds

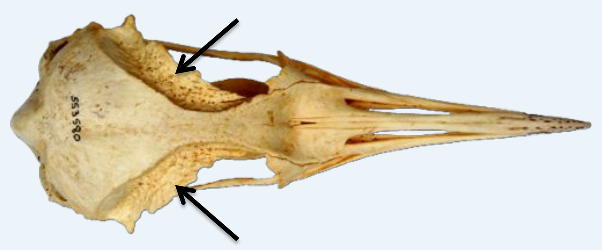
In penguins:

- Salt glands are located at the top of the skull in a depression above the eye
- All birds have salt glands, but they are enlarged in seabirds. The larger the salt gland, the higher the inferred salt intake

What do penguins eat?

- Teleost fish, which are hyposmotic with (less salty than) seawater, and marine invertebrates (squid and crustaceans), which are isosmotic with (as salty as) seawater. Per unit energy, marine invertebrates have twice as much sodium chloride as teleost fish
- Different species of penguins have different proportions of less-salty fish to salty squid/crustaceans in their diets

Previous studies have linked salt gland size in wetland and shorebirds to ecological factors such as habitat salinity and prey composition[7,8], but only limited work has examined relationships between salt gland depression size and ecology[5]. No studies have explored the causes of variable salt gland size among penguin species.



Driving Question:

Can the proportion of fish vs. marine invertebrates in a penguin species' diet be inferred from the size of the salt gland depression?

Methods

To quantify salt gland depression size relative to body size:

- 70 skulls from the Smithsonian National Museum of Natural History penguin skeleton collection, representing 15 of the 19 species of penguin, were used in this study
- Cranial length, width, and depth measurements were made both with calipers and the 3D digitizing data collection tool MicroScribe® G2X, while salt gland depression morphology was measured only using the MicroScribe
- Depression-to-body ratios were calculated using:
  1) a surface area measurement of the inner face of the salt gland depression; and
  2) a cranial size index derived from skull length and depth measurements, and used to correct for body size

To identify the influence of diet on salt gland depression size:

- Principal Component Analyses and statistical significance calculations were run using the software program R version 2.13.0
- Species averages for relative salt gland depression surface area were plotted against weighted, species averages of percent fish in diet taken from an extensive literature survey

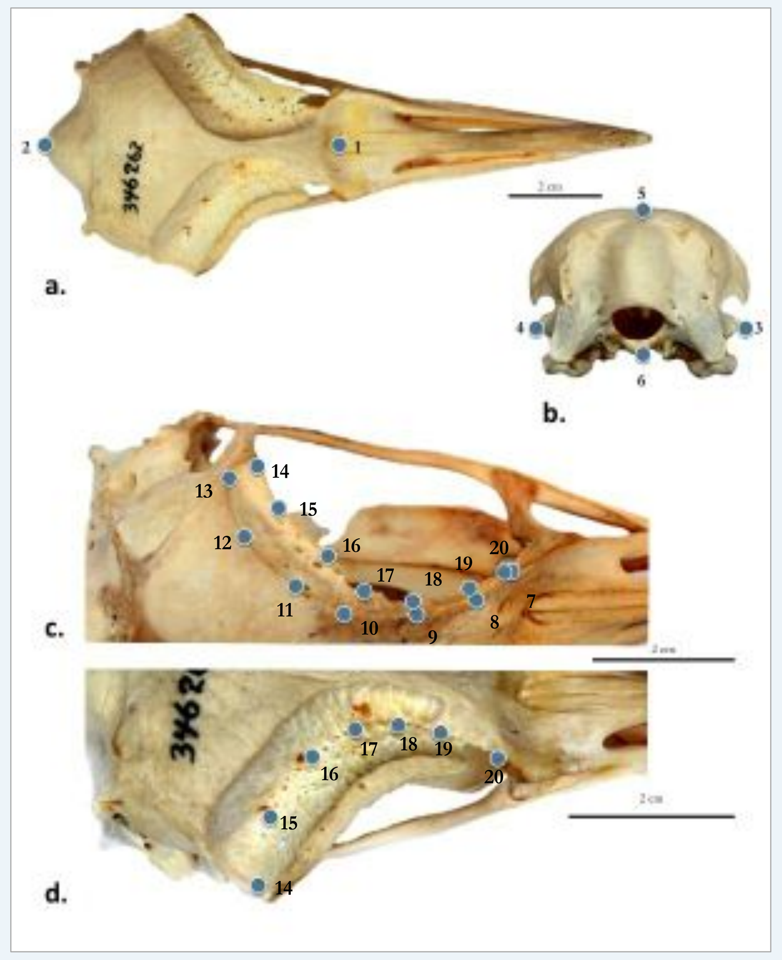


Fig. 1 — Measurements used in data analysis. Skull length (**a**) from nasal frontal hinge (1) to caudal extent of the occiput (2); maximum skull width (**b**) across the squamosals (3,4); and skull depth taken perpendicular to the palate from the dorsal skull vault (5) to the basitemporal plate (6). Landmarks 7–20 outline the inner face of the salt gland depression (**c**), delineated by the inner nutrient foramina in species with a dorsal shelf (**d**).

Results and Analysis

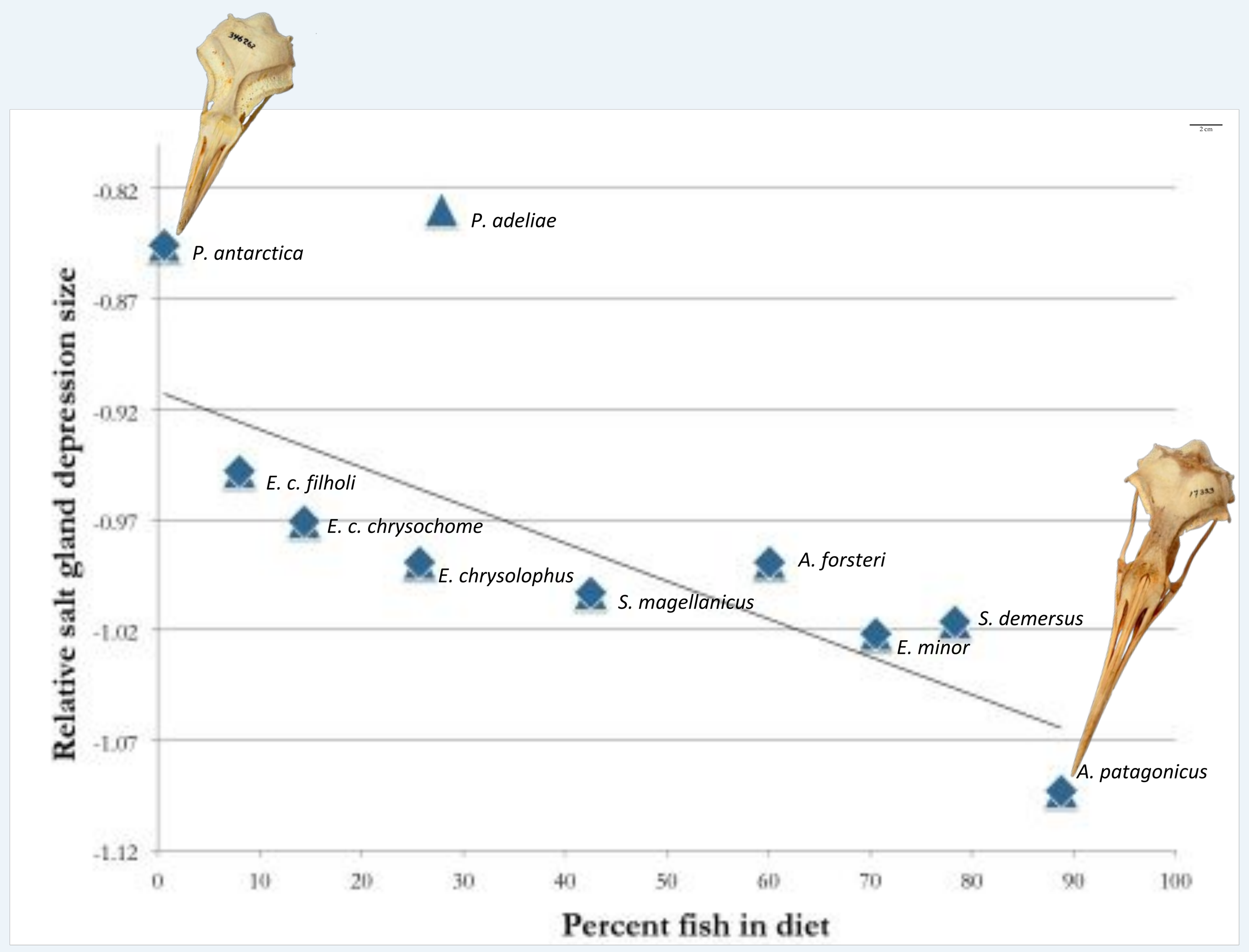


Fig. 2 — Relationship between relative salt gland depression size and percent fish in the diet of 10 penguin species. Relative salt gland depression size was calculated as the $\log_{10}$ of depression surface area divided by cranial size index. Percent fish in diet values calculated using weighted mean percent fish by species.

When outlier (shown as a triangle) Adélie penguin (*P. adeliae*) is removed from the data set, the p value of the regression slope is 0.004. The displayed trend line (r^2=0.71) reflects the data set with Adélie absent. When Adélie is included in the data set, the p value of the regression slope is 0.012 (r^2=0.52).

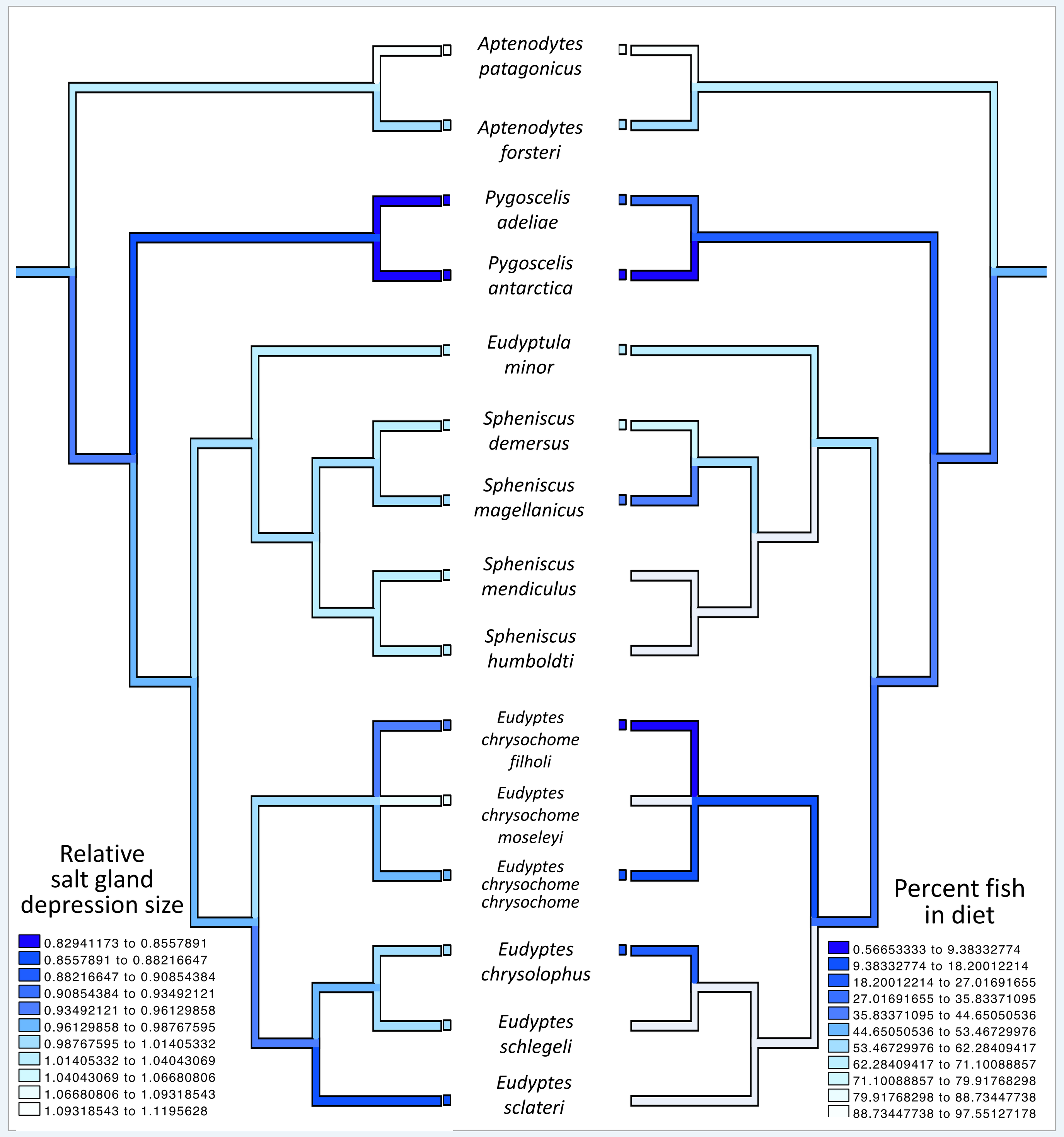


Fig. 3 — Reconstruction of ancestral character states for the continuous variables of log salt gland depression size (mm^{-1}) (left) and percent fish in diet (right). No diet data are currently available for the Galapagos *(S. mendiculus*), Humboldt (*S. humboldti*), Northern Rockhopper (*E. c. moseleyi*), Royal (*E. schlegeli*), or Erect-crested (*E. sclateri*) penguins (faded branches). Darker blues indicate larger relative salt gland depressions (left) and smaller percent fish in diet (right). Trees generated using Mesquite© 2.75.

Conclusions and Future Work

There is a good correlation between salt gland depression size (relative to body size) and diet, with larger salt gland depressions correlating with a diet high in isosmotic marine invertebrates, and smaller salt gland depressions correlating with a diet high in hyposmotic fish.

Because salt gland depression enlargement probably occurred several times throughout penguin evolutionary history, diet and depression size seem to be strongly related in a functional sense (as opposed to in a phylogenetic sense).

However…

In order to achieve a biologically significant sample size, additional specimens from the American Museum of Natural History will be measured. Because the inverse relationship between salt gland depression size and the percent of fish in the diet identified by this preliminary work is statistically significant at a 95% confidence level, we are optimistic about the final outcome of the study.

Avenues for further research:

- **Ecology vs. Phylogeny:** The relationship between salt gland depression size and other variables, such as biogeography, habitat salinity, and phylogeny, will be analyzed.
- **Adélie Penguins:** Why is the Adélie penguin an outlier? Some research suggests that they recently shifted from a mostly-fish to a mostly-krill diet. Potential within-species relationships will be explored.
- **Paleoecology:** The salt gland depressions of fossilized penguin skulls will be measured to make inferences regarding the diet of ancient penguins.
- **Conservation:** Research suggests there may be a correlation between hydrogen isotope values of seabird tissues and salt gland size[7]. We will continue to explore the use of hydrogen isotopes and skull morphology as means of studying human-induced changes to seabird diet.

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Penguin diet literature survey reference list available upon request.