Polar Biol (2003) 27: 56–58
DOI 10.1007/s00300-003-0563-3

SHORT NOTE

Victor Benno Meyer-Rochow · Jozsef Gal

Pressures produced when penguins pooh—calculations on avian defaecation

Received: 17 July 2003 / Accepted: 5 October 2003 / Published online: 31 October 2003

Abstract Chinstrap and Adélie penguins generate considerable pressures to propel their faeces away from the edge of the nest. The pressures involved can be approximated if the following parameters are known: (1) distance the faecal material travels before it hits the ground, (2) density and viscosity of the material, and (3) shape, aperture, and height above the ground of the *orificium venti*. With all of these parameters measured, we calculated that fully grown penguins generate pressures of around 10 kPa (77 mm Hg) to expel watery material and 60 kPa (450 mm Hg) to expel material of higher viscosity similar to that of olive oil. The forces involved, lying well above those known for humans, are high, but do not lead to an energetically wasteful turbulent flow. Whether a bird chooses the direction into which it decides to expel its faeces, and what role the wind plays in this, remain unknown.

Introduction

Penguins spend most of their life in the water. An extended period ashore only occurs during breeding. Anyone who has then watched a penguin fire a “shot” from its rear end must have wondered about the pressure the bird generates, but apparently no published data on the pressures produced exist. Since all penguins are protected and one must not approach penguins closer than 5 m (unless one holds a special permit), direct measurements are hard to come by. However, we found an indirect way to calculate the likely pressures involved in “venting” by chinstrap (*Pygoscelis antarctica*) and Adélie penguins (*P. adeliae*).

Brooding penguins, in order to relieve themselves, do not leave their stony nest, but move to the edge of it, stand up, turn their back nest-outward, bend forward, lift their tail, and shoot. The expelled material hits the ground maximally 40 ± 12 cm away from the bird and then leaves behind a whitish or pinkish streak that can end a few centimetres from the nest’s periphery and may be up to 1 cm wide. The colour of the streak depends on whether the penguin had enjoyed a meal of fish (mostly white) or krill (pinkish). According to Jackson (1992), the time required to excrete 50% of the total faecal mass is 9.1 h and 14.5 h for fish and prawn food, respectively.

From a few “spot-on” photographs, we estimated the aperture, from which the semi-liquid excretory material is released, to possess a maximal diameter of 8 mm at the moment of “firing”. Hind-gut diameters of 4.2 mm for the smaller rockhopper and 13.8 mm for the larger gentoo penguin are on record (Jackson 1992). Although the *orificium venti* generally opens through a horizontal slit in the Spheniscidae, the orifice becomes circular during evacuation (King 1981; Watson 1883). Since penguins, prior to venting, ascend the rim of pebbles that forms the edge of the nest, and are then somewhat higher than their surroundings, we place the elevation of the cloaca 20 ± 6 cm above ground (Fig. 1). By adopting average (= typical) values, we can mathematically examine which pressures would have been needed to achieve the faecal distances we measured around a penguin’s nest. The model would then allow comparisons between the “penguin-generated” pressures and those other organisms produce in connection with the propulsion of fluid or viscous material in narrow tubes, e.g. urine, seminal fluid, blood and, of course, faeces.

Methodological approach and results

The initial physical parameters used for our calculations were: maximum distance reached by the faeces, $l = 0.4$ m; diameter of vent at maximal distension, $d = 0.008$ m; height of vent above surrounding surface, $h = 0.2$ m. The velocity of the droppings can then be calculated by $v = l\sqrt{(g/2h)}$ (normal shot, $g \approx 10$ kg·m/s^2) as

---

V. B. Meyer-Rochow (✉) · J. Gal
Faculty of Engineering and Science, International University Bremen (IUB), P.O. Box 750561, 28725 Bremen, Germany
E-mail: b.meyer-rochow@iu-bremen.de

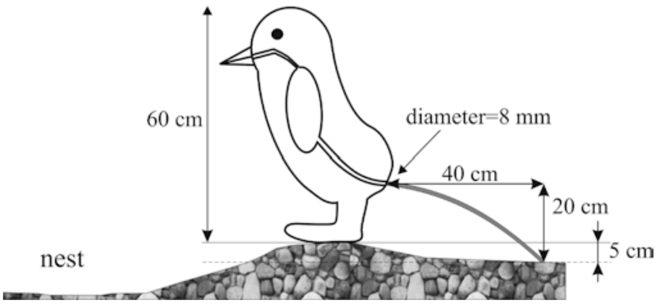


Fig. 1 Position of model penguin during defaecation and physical parameters used to calculate rectal pressure necessary to expel faecal material over a distance of 40 cm

2.0 m/s. The volume of the droppings was determined as $V = lr^2\pi \approx 2{\cdot}10^{-5}$ m^3 ($r = d/2 = 0.004$ m, radius of gut; $\pi \approx 3.14$), and the time required for defaecation as $t = 0.4$ s.

In the first approximation, we considered penguin droppings as "ideal", non-viscous fluids. In this approximation, the intestinal pressure during defaecation was used only to accelerate the mass from zero velocity to the velocity v, which is equal to 2 m/s initially, but then decreases gradually during the defaecation time t, without any loss of energy (ideal fluid). In this case p_a, the initial pressure of acceleration needed, is:

$$p_a = \frac{\rho v \Delta t A v}{\Delta t A} = \rho v^2$$

where A is the area of cross-section of vent and Δt represents an infinitesimally short time interval.

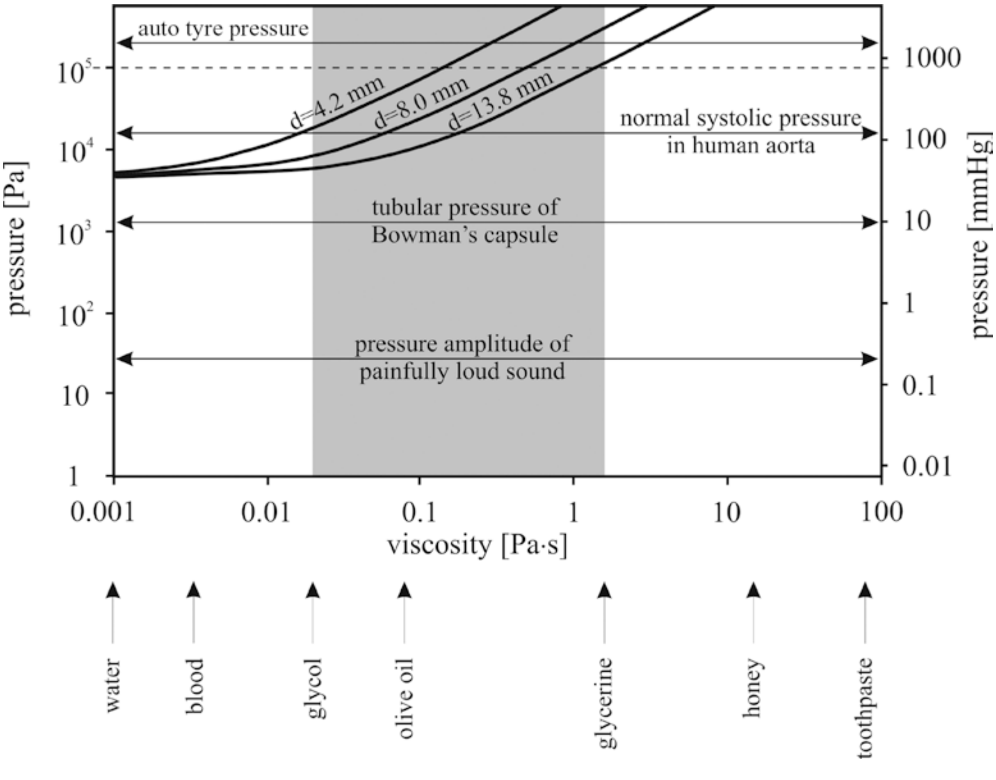
The resultant initial pressure now $p_a = 4.6$ kPa (about 34 mmHg), thus corresponds to the pressure that one can measure at the bottom of a water column with a height of about 46 cm. The pressure decreases in concert with the decrease of the outflow velocity. If the outflow velocity were constant during defaecation, then the expulsion of the droppings would resemble a fountain, which of course does not fit the observed faecal removal pattern.

In the second approximation, we considered the droppings to represent a viscous fluid with dynamic viscosity η. In this approximation, the intestinal pressure during defaecation would not only be used to accelerate the mass from zero velocity to 2 m/s, but also to help dissipate energy created by internal friction present in the viscous fluid (dynamic pressure). In this case, the Hagen-Poiseuille-equation (Rajagopal and Truesdell 2000) has to be applied, so that for the pressure p_b we obtain:

$$p_b = 8\frac{\eta l V}{\pi r^4 t} = 8\frac{\eta l^2}{r^2 t}$$

The initial pressure a bird needs to generate during defaecation was in the end approximated by the sum of p_a and p_b(p_o is the pressure outside): $p_s + p_o = p_a + p_b + p_o$. The pressure gradient $p_s = p_a + p_b$ needed to shoot out the faeces now depends strongly on the viscosity of the faeces. Figure 2 shows the dependence of the "expulsion pressure", p_s, on η, the viscosity of the droppings. Several attempts to measure faecal viscosities with a high-performance viscosimeter (Bohlin Instruments) were

Fig. 2 Rectal pressure (in Pa along *left* and mmHg along *right* ordinate) in relation to viscosity (*abscissa*) and three cloacal apertures (4.2 mm = rockhopper, 8.0 mm = Adélie, and 13.8 mm = gentoo penguin). The viscosity of penguin faeces lies between glycol and olive oil. For comparison, known viscosities of other substances are given along the *abscissa*



made, but owing to small remnants of crustacean cuticle, fish bones and scales, as well as other tiny fragments of solid material, the readings were inconsistent. Our best estimate for the semi-liquid faeces of the penguin is a viscosity that lies between that of glycol (lower value, $\eta = 0.02$ Pa s) and considerably below that of glycerine (upper value, $\eta = 1.5$ Pa s: Landolt and Börnstein 1955). That of olive oil ($\eta = 0.08$) seems a fair approximation. We conclude that fully grown chinstrap and Adélie penguins generate pressures between 10 kPa (77 mmHg) and 60 kPa (450 mmHg) during the evacuation of their faeces on land. The process of defaecation commences with the highest pressure initially and then rapidly drops to zero, hence the production of faecal streaks (and not "blobs"). In water, different parameters would apply, although (as in air) the smaller the cloacal diameter, the higher the pressure.

Cautionary conclusions

The pressures calculated by us and those actually developed by the birds in the field could be discrepant: (1) a consideration of peristaltic events in the gut (with non-Newtonian mechanisms of mucus participation, non-homogenous media inside the intestine, a certain amount of gut-wall elasticity, specific reflux zones, etc.: Yin and Fung 1971; Najarian and Niroomand 2000) could result in a more accurate determination of the internal pressure prior to evacuation, but unfortunately most of the necessary input parameters are unknown. (2) Our calculation revealed pressures valid only for laminar flow and they occur when the Reynolds number $= pdv/\eta$ is less than ca. 2,000. In our calculation with $\rho = 1{,}141$ kg/m^3, $d = 0.008$ m, and $v = 2$ m/s, the criterion for laminarity is met if $\eta > 0.009$ Pa s. Attention to the Reynolds number allows us to predict that greatly increased density, and/or diameter of gut, and/or flow velocity of the material would change the dynamics from laminar to turbulent. That would, of course, require much higher pressures to achieve the same range.

Birds, generally, possess shorter intestines than mammals, and in penguins the rectum is a straight tube (McLelland 1981). To raise intra-abdominal pressures and open and close the cloaca, three muscles are involved: *m. sphincter cloacae*, *m. levator cloacae*, and *m. transverses cloacae* (King 1981). The pressures on the rectal muscles in an upright human amount to 20 mmHg and are resisted by the rectal muscles, but when pressures reach 55 mmHg, the external as well as the internal sphincter relaxes and the contents of the rectum are expelled (Ganong 1999). During straining, pressures may rise well above 100 mmHg (Langley and Cheraskin 1958), but it would seem that the pressures regularly produced by penguins to expel their faeces on land are considerably greater, possibly reaching half an atmosphere.

All birds, penguins included, spend a considerable time preening and cleaning their feathers. It seems therefore that these birds propel their faeces as far away as possible (with a minimum amount of effort) lest they soil their plumage. Birds could theoretically increase their projectile defaecation range by squirting 45° upwards. However, their upright posture and position of the vent prohibit this in penguins, but in eagles and other birds-of-prey the squirt is, indeed, directed upward by ca. 15–30° (unpublished observation). The forces involved apparently do not lead to an energetically wasteful turbulent flow. It is interesting to note that the streaks of the faecal material radiate from the edge of the nest into all directions (no preference is noticeable). Whether the bird deliberately chooses the direction into which it decides to expel its faeces or whether this depends on the direction from which the wind blows at the time of evacuation are questions that need to be addressed on another expedition to Antarctica.

Acknowledgements We wish to thank Dr. Sören Scheid (Institut fur Umweltverfahrenstechnik, Universität Bremen, Germany) for his assistance with the viscosity measurements, and the New Zealand University Grants Committee, as well as the Chilean Antarctic Program (INACH), the last for their support of the first Jamaican Expedition to Antarctica.

References

Ganong WF (1999) Review of medical physiology. Appleton and Lange, Stamford

Jackson S (1992) Do seabird gut sizes and mean retention times reflect adaptation to diet and foraging method? Physiol Zool 65:674–697

King AS (1981) Cloaca. In: King AS, McLelland J (eds) Form and function in birds. Academic, London, pp 63–105

Landolt H, Börnstein R (1955) Material values and mechanical behavior of non-metals. In: Schmidt E (ed) Numerical data and functional relationships in science and technology, vol IV/1. Springer, Berlin Heidelberg New York

Langley LL, Cheraskin E (1958) The physiology of man. McGraw Hill, New York

McLelland J (1981) Digestive system. In: King AS, McLelland J (eds) Form and function in birds. Academic, London, pp 70–181

Najarian S, Niroomand H (2000) Peristaltic transport of a power-law fluid with variable consistency. 12th Conf Europ Soc Biomech, Dublin

Rajagopal KR, Truesdell CA (2000) An introduction to the mechanics of fluids. Springer, Berlin Heidelberg New York

Watson M (1883) Report on the anatomy of the Spheniscidae collected during the voyage of H.M.S. Challenger. Report on the Scientific Results of the Voyage of H.M.S. Challenger (Zoology), vol 7

Yin FCP, Fung YC (1971) Comparison of theory and experiment in peristaltic transport. J Fluid Mech 47:93–112