THEORETICAL AND EXPERIMENTAL STUDIES OF ENERGY EXCHANGE FROM JACKRABBIT EARS AND CYLINDRICALLY SHAPED APPENDAGES

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ABSTRACT Convection properties of jackrabbit ears were examined in a wind tunnel and in the field in an attempt to study the possible thermal role of the large ears. This work was part of a study on energy exchange of appendages. Cylindrical copper models of various shapes, aluminum castings of domestic and jackrabbit ears, and an amputated jackrabbit ear were studied in a wind tunnel (*a*) to define the range for convective heat loss for appendages of various shapes, and (*b*) to study the effect on convection of model shape and orientation to the wind. Shape, i.e. length and closure, proved important. Orientation to the wind produced no consistent or significant variation in the convection coefficient. The convection coefficients from the ear castings fell within the range generated from the cylindrical models. The convection coefficients for the amputated rabbit ear fell partially within the range. Net thermal radiation loss at midday from the jackrabbit ears was found to be small. Convection from the ears, however, could account for the loss of over 100% of the animal's metabolic heat at an air temperature of 30°C. If air temperature exceeds body temperature, the animal must either store heat or resort to the evaporation of water.

INTRODUCTION

Animal appendages come in a variety of shapes and sizes. Because of changes in wind direction outdoors and also different postural adjustments of appendages by animals, a quantitative analysis of heat transfer of appendages is difficult. The problem can be approached by starting with stylized appendages of different geometric configurations, e.g. cylinders and cones with varying degrees of closure, and determining the convective and radiative heat transfer properties for the extremes of orientation in respect to wind and radiation sources in the environment. The first section of this paper reports part of the results of studies we have undertaken to establish the maximum possible range of variation we could expect in heat transfer properties of the different geometries commonly found in cylindrically shaped appendages. We discuss here experiments on long and short cylinders of different closures. We then compare the results from cylinders to results from a specific cylindrically shaped animal appendage, the rabbit ear.

Since heat transfer mechanisms, e.g. radiation, convection, and evaporation, take place across a surface, large additional areas provided by some animals' appendages may be significant in the energy balance of these animals. It has been suggested (Schmidt-Nielsen, 1964; Schmidt-Nielsen et al., 1965) that the prominent ears (Fig. 1) of the jackrabbit may enhance thermoregulation. They suggested that the ears may help an animal to transfer excess heat through convection and radiation, thus saving precious water for evaporation.

Loss of heat through convection and radiation, however, is possible only as long as animal surface temperature remains above environmental temperatures. When the situation is reversed and environmental temperatures exceed the animal's surface temperature, additional surface area could become a liability to the animal since heat would flow into, instead of out of, the animal at this time. The animal's ear, however, has been reported (Schmidt-Nielsen et al., 1965) to undergo vasoconstriction in this situation, causing a reduction in "active" surface area.

The rabbit ear thus may increase the animal's active heat transfer surface when it is advantageous to increase energy flow from the animal. Presumably, the extra surface area could also be useful in warming a cold animal which by changing position or location might encounter warmer air or increased radiation. In either case, a surface which can be reduced or increased enables an animal to make better use of its

FIGURE 1 Jackrabbit, *L. californicus*, in one of its habitats, the Mojave Desert.

thermal environment. The adaptive value of such "optional" or increased surface area for heat transfer may be significant, particularly in an environment of extreme daytime heat and variable nocturnal cold such as the desert, where the jackrabbit lives.

Since appendage area is not part of the animal's permanently active surface, the energy budget of the appendage must be computed separately and added to the energy budget of the torso. Such calculations comprise the last part of this paper where we compare convective and radiative heat loss of the jackrabbit ear and the ability of the ears to dissipate metabolic heat production.

MATERIALS AND METHODS

The study was undertaken in four steps.

I. Models

Convection coefficients of eight gold-plated copper models were determined. The models, which are pictured in Fig. 2, are variations of ear shapes of animals like rabbits, chinchillas, and many other animals. The models differ in length/diameter ratios and in the perimeter length for identical curvatures. We used two length/diameter ratios of 6 and 1 and four different closures ranging from a completely closed cylinder to a one-fourth cylinder. The complete dimensions for each half-cylinder are presented in Table I.

Convection coefficients for each model were determined at various wind speeds in a wind tunnel in our laboratory. For the experiments, the model was mounted on a wooden sphere in the wind tunnel to simulate its relationship to an animal's head. Model temperature was measured with copper-constantan thermocouples which were soldered to the base. The procedure was to heat the model with an air-blowing heating gun to about 20°C above air temperature and then allow it to cool at a constant wind speed. The difference in temperature between the model and air was recorded on an Esterline Angus recorder (1 mv or 25°C full scale; Esterline Angus Div., Esterline Corp., Indianapolis, Ind.). Airspeed was monitored by a Hastings hot wire anemometer (Hastings-Raydist, Inc., Hampton, Va.). Air temperature and barometric pressure were measured to compute fluid properties of air.

The equation describing the rate of cooling of the model is derived from the first law of thermodynamics:

$$\text{Energy}_{\text{in}} + \text{Energy}_{\text{generated}} = \text{Energy}_{\text{out}} + \text{Energy}_{\text{stored}} \,. \tag{1}$$

The solar input is zero in the wind tunnel tests, and the thermal radiation input is considered in the net radiation term. Since no energy is generated in the model the equation reduces to

$$\text{Energy}_{\text{out}} = -\text{Energy}_{\text{stored}} \,. \tag{2}$$

Energy flowing out of the system is the sum of the convective and net radiative heat losses, $h_t A(T - T_\infty)$, where h_t is the total heat transfer coefficient, A is the total surface area, T is the model temperature in degrees Centigrade, and T_∞ is the temperature of the radiative and convective environment. The stored energy is $mc(\mathrm{d}T/\mathrm{d}\tau)$ where m is the mass, c is the specific

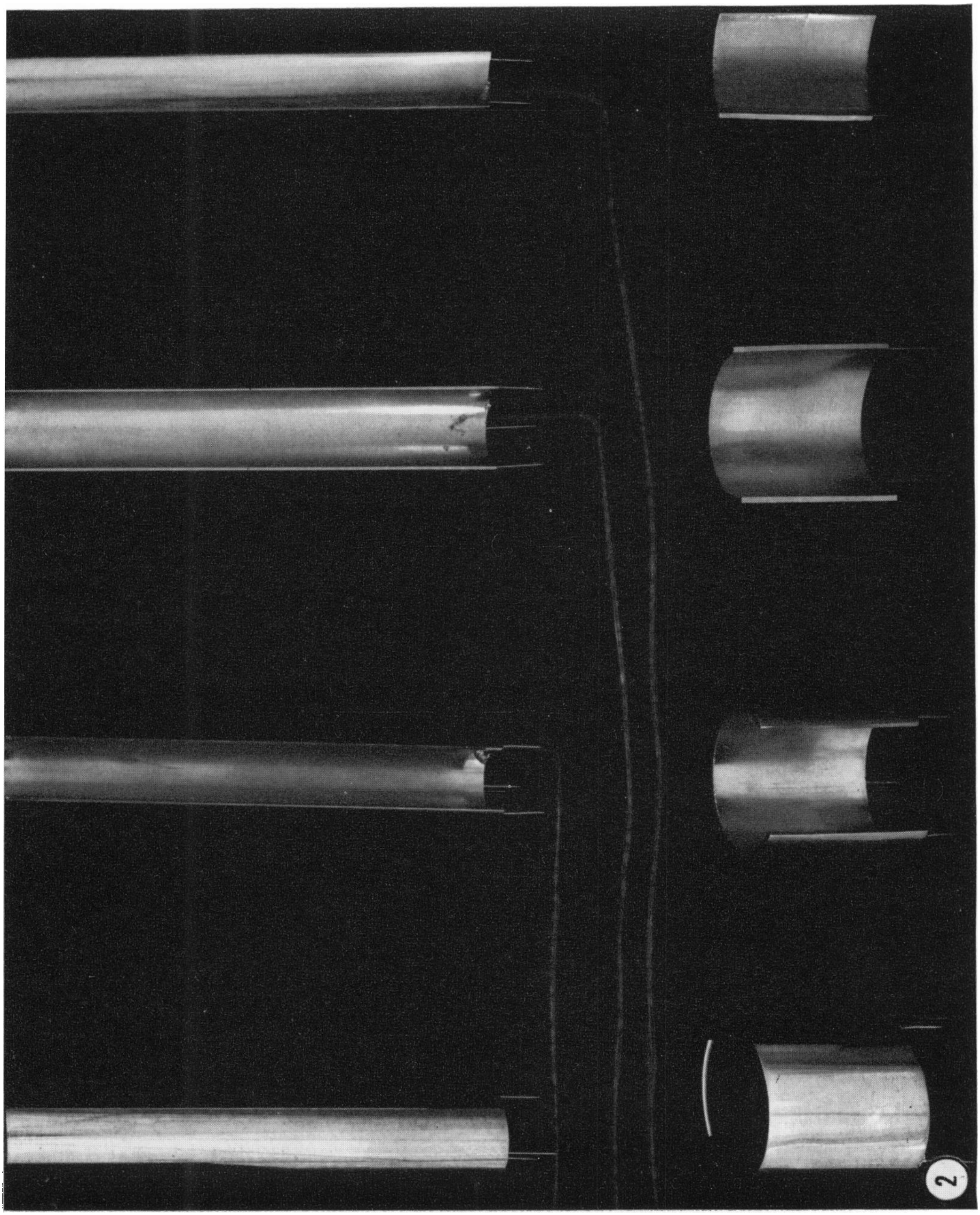


FIGURE 2 The gold-plated copper models used in wind tunnel experiments.

TABLE I

DIMENSIONS

	Diameter	Length	Area	Mass
	cm	*cm*	*cm*^{2}	*g*
Half-cylinder (long)	2.8	17.1	150.2	18.1
Half-cylinder (short)	5.2	5.3	86.5	80.6
Casting (domestic ear)	3.0	9.6	75.0	36.5
Rabbit ear (amputated)	5.0	13.5	150.0	4.0
Casting (jackrabbit ear)	5.0	13.5	150.0	70.2

The heat capacity for the copper cylinders was 0.091 and for the aluminum casting, 0.21. The heat capacity for the rabbit ear was considered to be the same as water, 1.0. The diameters of the rabbit ears and castings were measured at the widest point.

heat, and τ is time. Substituting the mechanism equations into equation 2, the equation becomes

$$h_t A(T - T_\infty) = -mc\frac{\mathrm{d}T}{\mathrm{d}\tau}. \tag{3}$$

Rearranging and integrating from the initial temperature T_i at initial time τ_i to the model temperature T at any time τ yields the form used to compute h_t :

$$h_t \int_{\tau_i}^{\tau} \mathrm{d}\tau = -\frac{mc}{A}\int_{T_i}^{T}\frac{\mathrm{d}T}{(T - T_\infty)}, \tag{4}$$

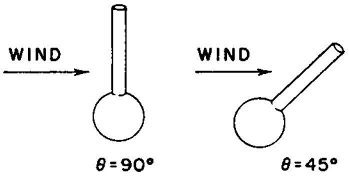
(or)
$$h_t = -\frac{mc}{A}\left(\ln\frac{T - T_\infty}{T_i - T_\infty}\right)\frac{1}{\tau - \tau_i}. \tag{5}$$

To find h_c, the convection coefficient, the radiation term in the heat transfer coefficient must first be determined. The mechanism equation for the net thermal radiation is

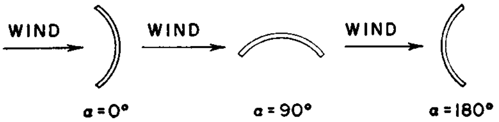
$$q_{\mathrm{rad}} = \epsilon\sigma A\hat{F}_{m-\infty}(T^4 - T_{\mathrm{rad}}^4), \tag{6}$$

where ϵ is the emissivity of the model, σ is the Stefan-Boltzmann constant, $\hat{F}_{m-\infty}$ is the view factor from the model to the environment, and T_{rad} is the radiant tempertature of the environment in degrees Kelvin. The net radiation for the model is negligible because the emissivity of the polished gold-plated models is 0.02 (Gubareff et al., 1960) and the reflectivity to thermal wavelengths is 0.98 thus making both the emission and absorption of thermal energy very small. The over-all convection coefficient h_t is essentially equal to h_c, the convection coefficient, and is readily calculated from the temperature-time data from the recorder and the area, mass, and specific heat from the model according to equation 5. The environment temperature T_∞ equals air temperature. A least squares routine was used to determine the best value of h_c.

The models are curved to some degree, as are real ears, and the orientation may affect airflow and heat transfer. The models were tested at three different rotational orientations to the wind (yaw angles) and at pitch angles of 90 and 45° as shown in Fig. 3.



Pitch angle viewed from side



Yaw angle viewed from above

FIGURE 3 Pitch angles of 90 and 45° viewed from the side; yaw of 0, 90, and 180° viewed from above.

II. Casting of Domestic Rabbit Ear

The second part of the study was to evaluate the convection coefficient of an aluminum casting of a domestic rabbit ear. The rabbit ear was amputated from a dead Belgian hare and cast in aluminum.[1] The ear casting was run at the same three yaw angles and two pitch angles as the copper models. The aluminum used in the casting was estimated to have an emissivity of 0.1 (Gubareff et al., 1960), and radiation could not be neglected as it was in the gold-plated models.

Total heat flow to the environment may be expressed using an analogy to Ohm's law for current flow, in which the voltage times the conductance equals current flow. The heat flow to the environment is the sum of the heat flows by radiation and convection. The radiant temperature difference between casting and environment and the temperature difference between casting and air temperature are analogous to voltage. The over-all conductance h_tA, is the sum of the parallel conductances for radiation and convection, h_rA and h_cA respectively. Thus

$$(h_tA) = (h_rA) + (h_cA). \tag{7}$$

The area is the same for each resistance and thus

$$h_t = h_r + h_c\,. \tag{8}$$

The radiant heat transfer coefficient h_r is defined in terms of q_{rad}, the net radiative heat loss:

$$h_r = \frac{q_{\text{rad}}}{A(T - T_{\text{rad}})}\,. \tag{9}$$

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[1] Beckman, W. A., J. W. Mitchell, and W. P. Porter. 1971. A.S.M.E. Paper 71-WA/HT-35.

The mechanism equation for net radiation in a black environment is

$$q_{\text{rad}} = \epsilon\sigma A\hat{F}_{m-\infty}(T^4 - T_{\text{rad}}^4), \tag{10}$$

$$h_r = \epsilon\sigma\hat{F}_{m-\infty}(T^2 + T_{\text{rad}}^2)(T + T_{\text{rad}}). \tag{11}$$

The term $\hat{F}_{m-\infty}$, or "F-hat," is the sum of all direct and internally reflected (within the cylinder concavity) rays that reach the environment (Beckman, 1968) and is approximately 0.8. The total area was determined using the casting as an electrode in an electrolytic bath, with current flow being proportional to surface area.

The radiation temperature T was 310°K, an average radiation temperature for the casting, and the temperature of the environment was approximately room temperature, 298°K. As the casting cools, the radiation coefficient varies from 0.00076 cal/cm^2-min°C at 318°K to 0.00070 at 298°K. The radiation coefficient at the average temperature of 310°K was calculated from equation 11 to be 0.00073. The convection coefficient is then computed from equations 5 and 8.

III. Casting of Jackrabbit Ear

The next part of the study was to determine the convection coefficient of a casting of a jackrabbit ear. The casting was made using the same technique as for the domestic rabbit ear. It was then run in the wind tunnel at the six different orientations to the wind already described. Since this casting was gold-plated, thermal radiation was neglected.

IV. Real Jackrabbit Ear

The fourth part of the study was to evaluate the convection coefficient of a real jackrabbit ear in the wind tunnel. The jackrabbit ear was amputated from a *Lepus californicus* road kill in Nevada. The rabbit ear was placed in the wind tunnel with convex side of the ear normal to wind flow. An aluminum foil shield was constructed to protect the ear from direct blasts of heat from the heating gun. Cooling curves were then obtained using the same procedure as used in sections I, II, and III.

The ear thermocouple was placed in a shallow cut made in the concave part of the ear and sewn into the ear with cotton thread. Since the amputated ear has no blood to maintain it at a uniform temperature along its length, an ear was instrumented with three thermocouples along its length, heated up, and cooled with a fan. The maximum temperature variation along the ear was never more than 3°C, and the ear can be treated as being isothermal. The temperatures used in the data reduction were taken from a thermocouple placed midway along the length of the ear.

The radiation coefficient was calculated for the amputated rabbit ear using an emissivity of 1.0 (Hammel, 1956), and is 0.0073 cal/cm^2 °C min. The area was determined from a tracing. The convection coefficient was then computed.

V. Evaluation in the Field

The final part of the study was to evaluate the relative effects of convection and radiation in the field. Two amputated *L. californicus* ears were instrumented with copper-constantan thermocouples and placed about 12 inches off the ground in an area where jackrabbits might sit. One ear was in the shade of a yucca, the other in direct sunlight. Periodic temperature readings of the ears were taken to determine the effects of the two thermal environments.

Several other environmental parameters were also measured periodically, namely, solar radiation, wind speed, air temperature, vegetation temperature, shaded substrate temperature, and unshaded substrate temperature. The bush thermocouple was placed in the shady part of a bush facing the ear. Air temperature was determined by a thermocouple shielded by aluminum foil and placed at approximately the same height as the ears. The ground thermocouples were placed on the ground and covered over with the thinnest possible sprinkling of sand. Temperatures were measured with a hand-balancing potentiometer. Wind speed was measured with a cup anemometer.

RESULTS

The convection coefficients h_c for two of the copper models and the castings are plotted in Figs. 4–7 as functions of wind speed V. Pitch and yaw angles do not have a consistent or significant effect on the convection coefficient, and the variation is approximately ±10%. Since this variation is within the range of experimental accuracy and within the range generated by the 95% confidence limits, the variation cannot be considered significant.

Moreover, the variation in convection coefficients cannot be consistently correlated to particular pitch and yaw combinations. For example, the highest convection

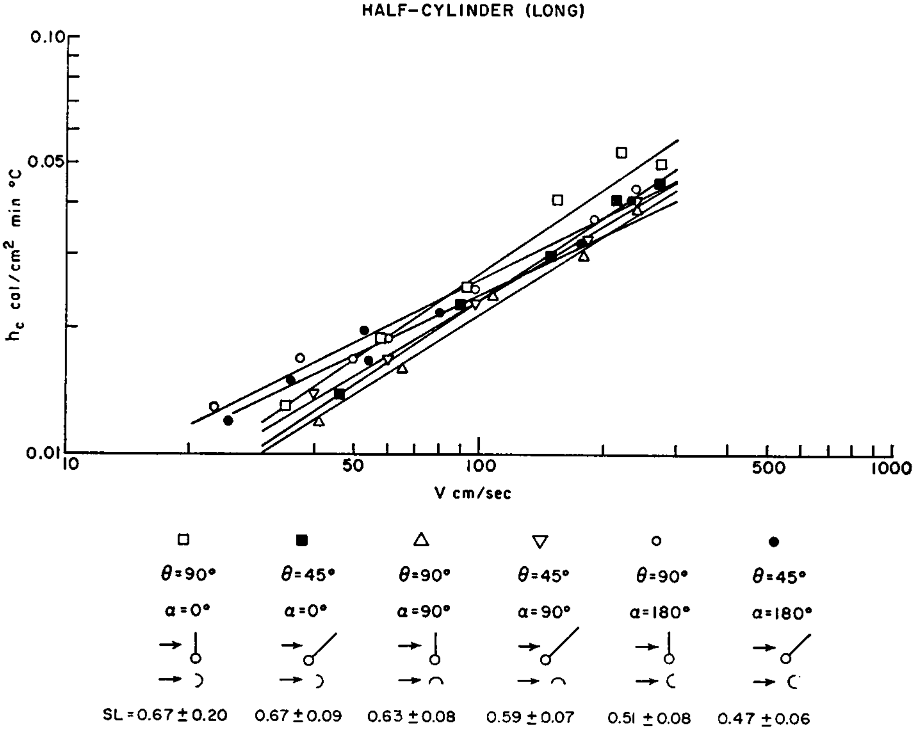

FIGURE 4 The convection coefficient h_c as a function of wind speed V for the half-cylinder (long) at all six combinations of pitch and yaw angles in the wind tunnel.

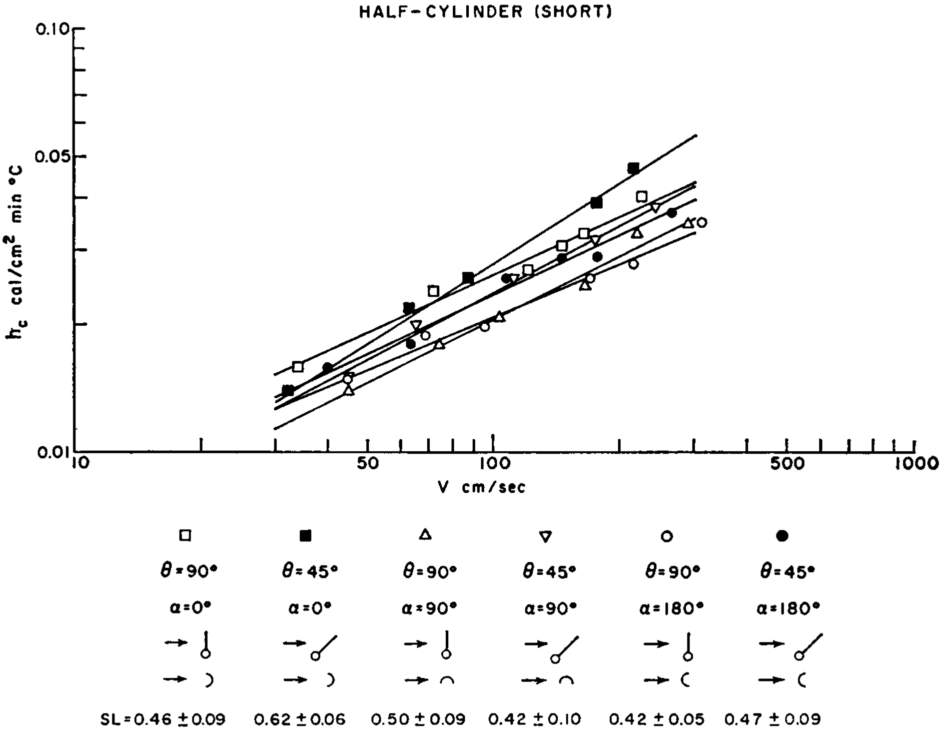

FIGURE 5 The convection coefficient h_c as a function of wind speed V for the half-cylinder (short) and all six combinations of pitch and yaw angles in the wind tunnel.

coefficient at 100 cm/sec, h_{100}, for the half-cylinder (long) occurs at a pitch angle of 90° and a yaw angle of 0°, but the same combination of pitch and yaw angles produces the lowest h_{100} for the casting. The variation in pitch and yaw angles then produces neither a consistent nor a significant variation in wind tunnel convection for the models. Additional data supporting this for the remaining six models will be presented elsewhere.[2]

Because of the overlap in confidence intervals, we averaged the results for all pitch and yaw angles for each of the eight cylinders. The least squares line for each of the cylinders is shown in Fig. 8.

It can be seen that the variation in convection coefficient is most pronounced in the long cylinders. The h_{100} for the ¼-cylinder (long) is higher by a factor of 1.80 than for the ¾-cylinder (long). The whole cylinder (long) and half-cylinder (long) have average convection coefficients which fall midway between the ¼- and ¾-cylinders (long) and are higher by a factor of 1.30 than the ¾-cylinder (long). The long model with the shortest perimeter, i.e. the smallest closure, has the highest convection coefficient.

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[2] Wathen, P., J. W. Mitchell, and W. P. Porter. Manuscript in preparation.

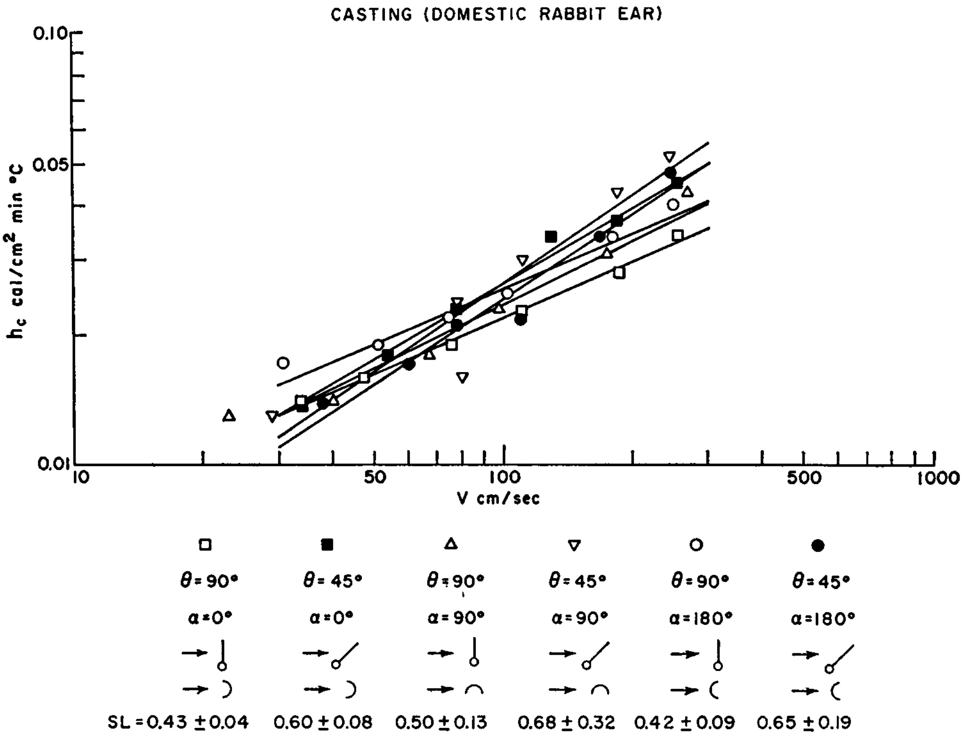

Figure 6 The convection coefficient h_c as a function of wind speed V for the domestic rabbit ear casting at all six combinations of pitch and yaw angles in the wind tunnel.

The variation in the short cylinders is not nearly so striking as in the long cylinders, having neither the high convection coefficients of the ¼-cylinder (long) nor the low convection coefficients of the ¾-cylinder (long). Instead all the short cylinders fall around the midline for the long cylinders. The greatest variation in the short cylinders is 20% which, when taking into account the confidence limits of the data, is not a significant variation.

There are, then, no large variations due to circumference in the short cylinders, but the h_{100} of long cylinders may vary up to 180%. It appears that length accentuates the effects of closure.

From Fig. 9 the convection coefficients of the ear, the domestic casting, and the models are seen to be all nearly the same. An equation describing h_c as a function of V can be developed which fits six of the models and the casting within ±10%. The general function describing the log-log plot is

$$h_c = k(V)^{\mathrm{SL}}, \tag{12}$$

where SL is the slope of the line and k is a constant. The slope determined by least

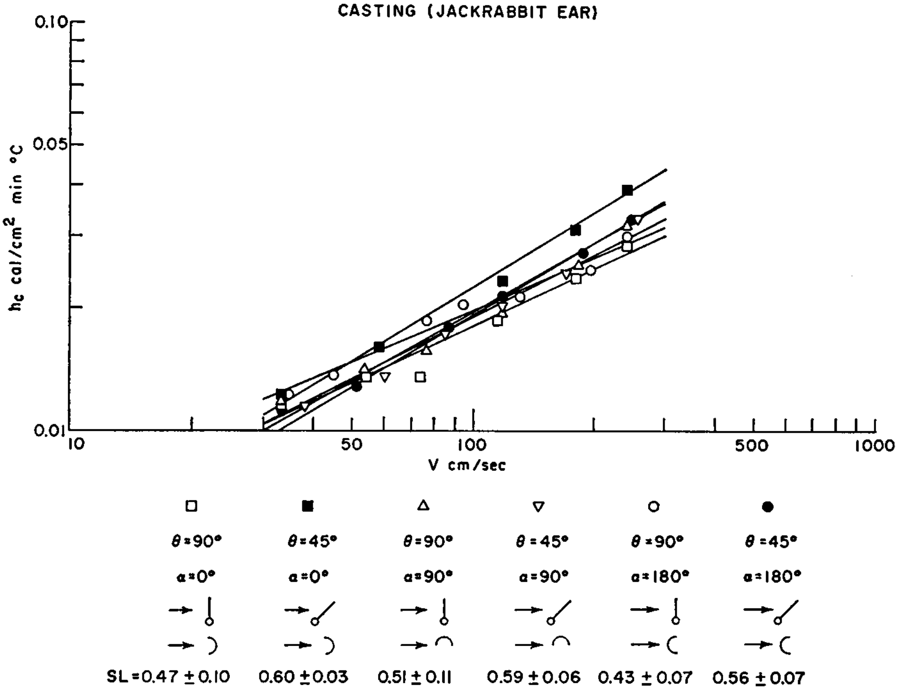

FIGURE 7 The convection coefficient h_c as a function of wind speed V for the jackrabbit ear casting at all six combinations of pitch and yaw angles in the wind tunnel.

squares analysis is approximately 0.5. Solving for k at $h_{100} = 0.025$, equation 12 becomes

$$h_c = 0.0025(V)^{0.5} \tag{13}$$

for the six models and the casting. The equations describing h_c as a function of V for the remaining two cylinders and the jackrabbit ear casting are:

$$h_c = 0.0020(V)^{0.5} \tag{14}$$

for the ¾-cylinder (long) and the jackrabbit ear casting, and

$$h_c = 0.0035(V)^{0.5} \tag{15}$$

for the ¼-cylinder (long).

These equations may be useful to predict the convection coefficients for rabbit ears for other situations.

A least squares line for the ear castings for all pitch and yaw angles is presented in Fig. 9 along with the points for the amputated rabbit ear in the wind tunnel. The

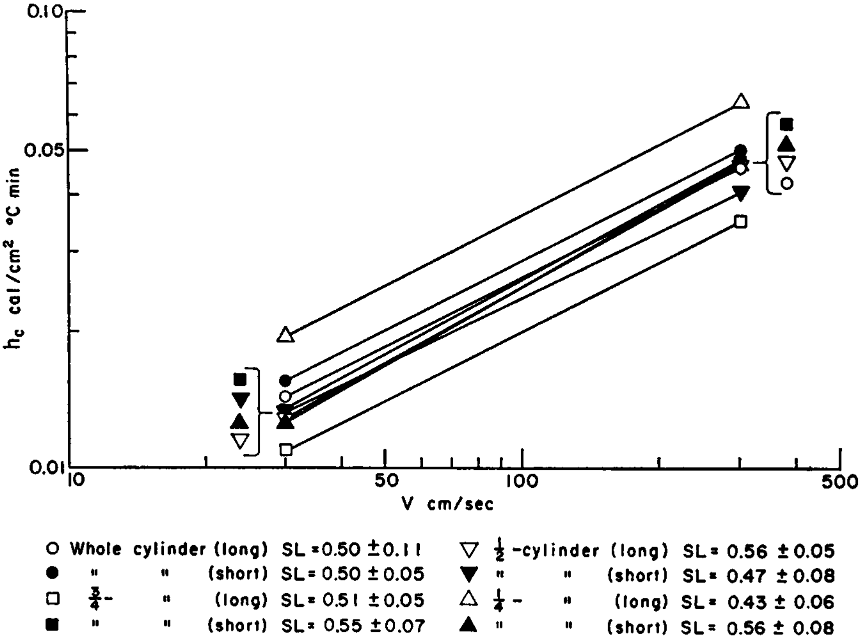

FIGURE 8 The convection coefficient h_c as a function of wind speed V with one curve for each of the eight cylinders in the wind tunnel.

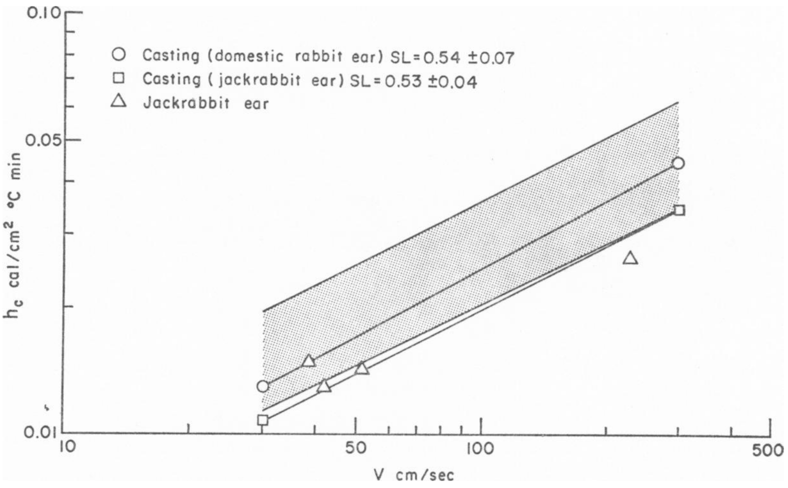

FIGURE 9 The convection coefficient h_c as a function of wind speed V in the wind tunnel for the amputated rabbit ear and the castings plotted against the range generated by the copper models.

domestic rabbit ear casting data fall within the range of the model data, and the jackrabbit ear and casting data fall partially within the range.

The jackrabbit ear casting has a lower convection coefficient than the domestic rabbit ear casting. Specifically, the h_{100} for the domestic rabbit ear casting is higher for the jackrabbit ear casting by a factor of 1.12; however, the jackrabbit ear casting agrees well with the four jackrabbit ear points. This suggests that the thin fur on the ear probably does not significantly affect the convective heat transfer properties.

The ear temperatures taken in the field are plotted in Fig. 10 along with other environmental parameters. The ear kept in the shade of a yucca bush remained within 2.7°C of air temperature while the ear receiving direct solar radiation rose to 10.8°C higher than air temperature during peak periods of solar radiation. Solar radiation is recorded in Table II. Highest unshaded ear temperatures were recorded in late afternoon when the animal would be receiving direct rays from near the horizon.

DISCUSSION

The wind tunnel tests have produced basic information on convection that applies to cylindrically shaped ears like those of the jackrabbit. The data show that the

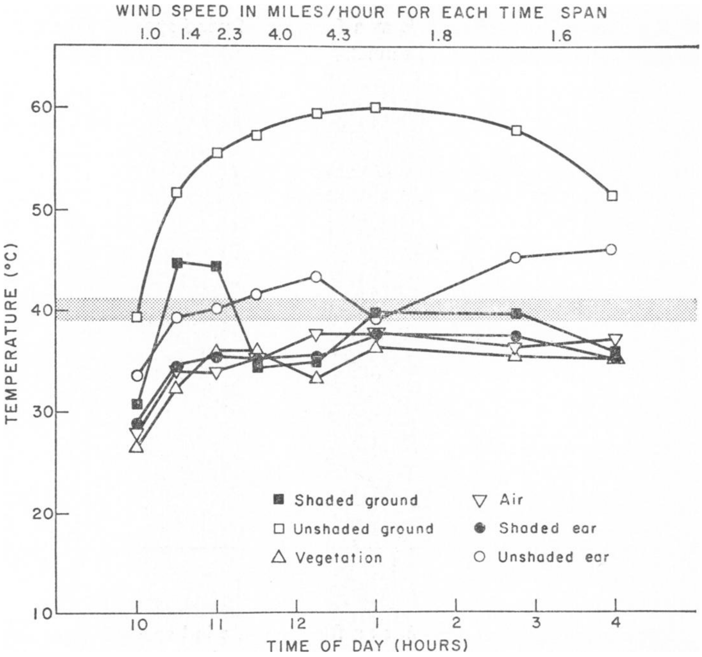

FIGURE 10 Temperatures of ground (shaded and unshaded), vegetation, air, and amputated rabbit ears (shaded and unshaded) for the midpart of the day 7 July 1970. The cross-hatched line is body temperature (Schmidt-Nielsen, 1964). Wind speed is given above in miles per hour.

TABLE II

SOLAR RADIATION 7 JULY 1970

Time	Radiation
hr	$cal\ cm^{-2}\ min^{-1}$
6	0.012
7	0.069
8:10	0.193
8:52	0.368
10:17	1.215
11:45	1.333
12:30	1.390
1:40	1.318
2:00	1.288
3:00	1.160
4:00	0.830
5:10	0.208

the flattest surface, i.e. the shortest perimeter, is the highest convector and that appendage length accentuates the effect produced by the flat surface.

The convection coefficients of the short cylinders fall consistently in the same range regardless of curvature. This may be accounted for by boundary layer–wake phenomena, but the specific mechanisms are not understood.

The circumference differences in the long cylinders indicate that more perimeter means less convective heat transfer per unit area in equivalent environments. If the inside area of the whole cylinder, which in the model is not exposed to the airflow, were included in the definition of h_c, the h_{100} of the whole cylinder would fall below that of the ¾-cylinder by 22 %. Then there would be a complete gradation in high to low convection from ¼- to whole cylinder. This trend may be partly because of the fact that the flattest cylinders also have the most active wakes.[3]

The models studied in the wind tunnel show no significant variation in average convection coefficient due to pitch and yaw angles. This should simplify further study as only wind speed is a parameter instead of both wind speed and direction. It should particularly enhance study of live animals which move their appendages with little regard for the experimenter's wind measurements.

We did not do convection experiments for pitch angles of 0° (ears laid flat against the back). The airflow over the ears in this situation would be greatly modified by airflow over the head or side or back of the animal depending on wind direction. The results would probably be very similar to those obtained from flow over flat plates. We assumed that if the ears were laid flat against the body they most likely would be there either because it was cold (vasoconstriction) or because the animal was alarmed. In either case, the animal would not be able to lose a maximum amount

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[3] Mitchell, J. W. 1971. *Trans. A.S.M.E.* In press.

of heat; this was a boundary condition we have attempted to establish in this paper. If the animal were in cold, still air and exposed to solar radiation, such a posture, however, might be ideal for gaining heat using the ears.

The ears of the jackrabbit (Fig. 1) grow up to 130 mm long in *L. californicus* and up to 173 mm in *L. alleni* (Hall and Kelson, 1959). The curvature of the actual ear varies from ¾- to a whole cylinder at the base to less than the curvature of a ¼-cylinder at the tip.

Comparison of the ears of the domestic rabbit with those of the jackrabbit show that the perimeter of the jackrabbit ear at the widest part is greater in relation to the length than that of the domestic rabbit ear. The difference in shape may be significant since the h_{100} of the casting of the domestic rabbit ear is 13% higher than that of the jackrabbit ear. From these data the domestic rabbit ear would be expected to be a better convector; however, since convective heat loss is the product, $h_c A(T - T_a)$, the jackrabbit ear would still be able to convect away more of its body heat, having approximately twice the area of a domestic rabbit ear. The desert jackrabbit appears to have evolved an efficient convector because it is long, approaches a flat surface near the tip, and has a large surface area.

The final part of this study demonstrates the effect of the environment on the animal. Solar radiation (Table II) is one of the largest energy flows into the animal and it is worthwhile to avoid this huge radiant input at almost all costs, predation and social factors notwithstanding. In the partial shade afforded by desert vegetation, the animal is able to avoid solar radiation and still take advantage of convection.

It is possible to calculate the relative contributions to heat loss from the ears by thermal radiation to the environment and by convection for a jackrabbit sitting in the shade. Schmidt-Nielsen et al. (1965) concluded that the ears could possibly radiate energy to the cold sky and possibly thereby dump large amounts of heat; however, the sky comprises only about one-third of what the ears "see." The ground comprises about another third and the vegetation the rest. The equation for net exchange of thermal radiation for the ears for this situation is

$$q_{\mathrm{rad}} = \epsilon\sigma A F_{\mathrm{e}-\infty}[\hat{F}_{\mathrm{e}-\mathrm{sky}}(T_{\mathrm{sky}}^4 - T_{\mathrm{e}}^4) + \hat{F}_{\mathrm{e}-\mathrm{veg}}(T_{\mathrm{veg}}^4 - T_{\mathrm{e}}^4) + \hat{F}_{\mathrm{e}-\mathrm{g}}(T_{\mathrm{g}}^4 - T_{\mathrm{e}}^4)]. \quad (16)$$

The subscripts e, veg, and g refer to ear, vegetation, and ground respectively. Ear area A is 320 cm^2 and $F_{\mathrm{e}-\infty}$ is 0.8 where we assumed it has the same value as a half-cylinder (Siegel and Howell, 1969). We assumed an air temperature of 35°C which was common in our study area. We computed a sky temperature of 24°C (Swinbank, 1963), a typical value for this time of day in the desert. Our observations of animals in the shade of bushes showed that most of the ground that the ears see is unshaded and at a temperature of 55–60°C. The vegetation temperature is typically about 40°C during midday. We assumed that the rabbit can hold its ear temperature at body temperature, 40°C. From equation 16, we find that the ears gain

TABLE III

METABOLIC HEAT DISSIPATION BY THE JACKRABBIT EAR

Air temp	Ear temp	Metabolism	Wind speed	Wind tunnel convection coefficient	Field convection coefficient	Convection	Convection/ metabolism	Blood flow
°C	*°C*	*cal/min*	*mph*	*cal/cm² °C min*	*cal/cm² °C min*	*cal/min*	*%*	*ml/min*
40	40.5	135	0.5–5.0	0.01–0.04	0.014–0.056	2.2–9.0	1.6–6.6	18
35	39.5	122	0.5–5.0	0.01–0.04	0.014–0.056	20–81	16–66	18
30	39.0	118	0.5–5.0	0.01–0.04	0.014–0.056	40–161	34–136	18

Areas of two ears of a 2.5 kg rabbit are assumed to be 320 cm². Values for ear temperature are assumed to be equal to body temperature. (Body temperature, ear area, and metabolism are from Schmidt-Nielsen et al., 1965.)

between 0.7 and 5.6 cal/min from thermal radiation exchange; the radiant heat loss to the sky is 12.8 cal/min while the radiation gain from the ground varies from 13.5 to 18.4 cal/min depending on whether the surface temperature of the ground is 55 or 60°C.

The airspeed varies from 0.5 to 5 mph (Fig. 10), and the corresponding wind tunnel convection coefficient varies from 0.01 to 0.04 cal/cm²-min°C (Fig. 7). In the field, the convection coefficient would be expected to be about 1.4 times higher than in the wind tunnel.[4] For air temperatures of 40, 35, and 30°C, body temperatures of 40.5, 39.5, and 39° C respectively can be expected (Schmidt-Nielsen et al., 1965). At these body temperatures metabolic heat production would be 135, 122, and 118 cal/min respectively for a 2.5 kg rabbit (Schmidt-Nielsen et al., 1965). For maximum heat loss, the convecting surface of the ear is maintained at body temperature by blood flow. Convection may then account for the loss of over half and possibly all of the metabolic heat at air temperatures of 30 and 35°C (Table III) and is an important avenue of heat loss until air temperature exceeds the convecting surface temperature. When this happens the animal in the open desert must either store heat or evaporate water. Radiation exchange will not maintain the energy balance of the animal during midday.

The ear blood flow required to transfer the metabolic heat can be estimated. The total cardiac output of a resting jackrabbit with a metabolic output of 120 cal/min can be calculated to be approximately 600 ml/min. This assumes 4 ml O_2/100 ml blood and 5 cal/ml O_2 (Selkurt, 1963). Blood flow can then be calculated using the formula

$$\text{Flow} = q_c/[c_{bl}(T_{in} - T_{out})], \qquad (17)$$

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[4] Mitchell, J. W., G. Jackson, and W. Porter. 1971. *Ecology*. In press.

where q_c is the maximum heat lost in calories per minute from the ears at the temperatures listed above, c_{bl} is the specific heat of blood and assumed equal to that of water, T_{in} is the temperature of the blood entering the ear in degrees Centigrade and assumed to be body temperature, and T_{out} is the temperature of the blood leaving the ear in degrees Centigrade and assumed to be air temperature. The blood flows required to carry metabolic heat to the ears are listed in Table III. The jackrabbit with a cardiac output of 600 ml/min should easily be able to pump enough blood to supply the ears' convective heat loss. The predictions in Table III are consistent with recently published experimental data by Nagasaka and Carlson (1971). The data in their Table 1 also indicate little or no heat production by metabolism of the ear tissue.

In our experiments with domestic rabbits at the University of Wisconsin Biotron, it was observed that when panting commences, the rabbit's ears begin to vibrate or twitch at the same frequency as the panting frequency. Perhaps this twitching requires very little energy as long as panting continues. In any case and for whatever "reason" it occurs, panting may serve to increase convection from the ear. It is suggested that experiments be conducted to see whether this twitching of ears occurs in the jackrabbit and under what conditions.

To determine more precisely the importance of convection from the jackrabbit's ears, it will be necessary to study the live animal further, behaviorally and physioogically. Presumably, the ears of the jackrabbit are only one of the adaptations which allow the species to survive in the desert. For example, when air temperature exceeds ear temperature and the ears are no longer of any convective value, the animal must either store heat or resort to other adaptations such as the evaporation of water. Specifically it will be interesting to discover the value of each of these adaptations in terms of the total energy budget of the animal.

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