COUNTERCURRENT HEAT EXCHANGE IN THE RESPIRATORY PASSAGES*

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One of the important functions of the upper respiratory tract is to condition the inspired air prior to its arrival at the lungs. This conditioning involves heating the air to body temperature and humidifying the air to full saturation at that temperature. As a consequence of conduction and evaporation, heat is lost from the nasal surfaces, and the temperature of these surfaces falls below body temperature. During expiration, therefore, air leaving the lungs at body temperature and full saturation is cooled as it passes along the respiratory tract.

This cooling of the expired air accomplishes a second function of the respiratory tract, that of conserving body heat and body water. Measurements of air and surface temperatures have been made in human respiratory passages by Seely in 1940 and later with improved techniques by Cole and by Inglestedt. These studies have demonstrated that, although air is expired at temperatures below body temperature, the human respiratory tract is not a very efficient heat exchanger. According to Cole temperatures in the central portion of the air stream near the nasal opening seldom are within 3°C of the surface temperature of the nasal passage at that location, and the mean temperature of the expired air of subjects breathing at normal room temperatures is about 33°C.

Previous studies have shown that the loss of water by evaporation from kangaroo rats (Dipodomys merriami), relative to the oxygen consumption, is lower than in man and lower than expected if the expired air were saturated at body temperature. This could theoretically be accomplished in two ways: (a) through a higher degree of utilization of alveolar oxygen before the air is expired, or (b) through expiration of air at a temperature considerably lower than that of the body. (A third possibility, that the air is not saturated by passage over the moist surfaces of the lung, seems highly improbable.) Studies of the oxygen loading characteristics of the blood as well as its carbon dioxide content excluded possibility (a). The present study was undertaken to make direct measurements pertaining to possibility (b).

Materials and Methods.—Temperatures were measured with small bead thermistors, 0.125-mm diameter. Resistance changes in the thermistor due to temperature changes were observed as voltage deflections on an oscilloscope connected across a simple Wheatstone bridge circuit. The bridge balance point was arbitrarily selected at a temperature midway in the anticipated temperature range.

Unanesthetized animals were restrained in a prone position on a board by means of loops of soft plastic tubing around the legs, neck, and snout. The thermistor was placed in the nasal passage by first inserting a length of polyethylene tubing (0.61 mm o.d.); the thermistor and leads were then inserted into the polyethylene tubing which subsequently was retracted, leaving the thermistor in place. Before insertion, the polyethylene tubing was lightly coated with topical xylocaine ointment to minimize irritation to the mucous membranes. The animal was then

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covered by a Lucite chamber through which air at controlled temperature and humidity was circulated.

The thermistor leads were taped to a rack and pinion device mounted horizontally in front of the animal's nose. This allowed a slow and calibrated withdrawal of the thermistor out of the nasal passage. The rectal temperature of the animal and the air temperature in the chamber were measured simultaneously with larger thermistor probes.

Cross sections of the nasal passages were obtained by making plastic casts of the respiratory tracts. The animal was etherized, and the nasal passages were filled with dental plastic impression material (Permlastic, Kerr Mfg. Co.) by retrograde injection into the trachea under moderate pressure. After allowing time for the plastic to set, the tissue was digested in acid solution (15–18% HCl) for about two days. The plastic cast was then fixed in paraffin, cut in sections of 1/2-mm thickness, and mounted on glass slides for study of the dimensions.

The studies were performed on two species of desert rodents from southern Arizona, Merriam kangaroo rat (*Dipodomys merriami*, 27–33 gm body weight) and bannertailed kangaroo rat (*Dipodomys spectabilis*, 90–100 gm). White laboratory rats were used for comparison.

**Results.**—Nasal temperatures of a kangaroo rat, *Dipodomys merriami*, are shown in Figure 1. The two curves, obtained while the animal was breathing dry air and saturated air, respectively, show the temperature profiles of the nasal passage. Curves representing rectal and chamber temperatures measured at the same time as the corresponding nasal temperature are included. At a depth of about 18 mm the nasal temperature was stable, although somewhat lower than the rectal tem-

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**Fig. 1.**—Nasal temperature of a kangaroo rat breathing moist air (triangles) and dry air (circles). Simultaneous rectal and ambient temperatures for the two experiments are plotted using the same symbols.
temperature. However, the temperature gradient toward the tip of the nose differed under the two conditions. In the animal breathing moist air, the gradient was about 0.5°C/mm, while in the animal breathing dry air the gradient was about 1.0°C/mm. The temperature just inside the nasal opening of the kangaroo rat inspiring dry air was 3°C below inspired air temperature, while the corresponding temperature in moist air was more than 1°C above the inspired air temperature. (Temperature fluctuations at a given depth associated with the respiratory cycle were negligible and seldom exceeded 0.2–0.3°C.)

The differences in temperature pattern between animals breathing moist and dry air was seen in all animals (eight Merriam kangaroo rats and four bannertailed kangaroo rats).

As a comparison, similar measurements were made on white rats, a rodent which normally does not experience an extreme scarcity of water in its environment. As illustrated in Figure 2, the nasal passages of the white rat have a temperature profile and therefore exchange heat in a way similar to that of the kangaroo rat.

A number of measurements were made in dry air at various higher and lower ambient temperatures (Fig. 3). The temperature gradient in the nasal passage became less steep as the air temperature was increased, but in all cases the temperature measured at the nasal tip was below the simultaneous ambient air temperature.

The measurements, although made with the smallest thermistors available, do not directly give the temperature of the expired air, but rather a composite measurement of wall and air temperature. In order to evaluate the heat exchange between passing air and the walls, it was necessary to know the dimensions of the passageways. In kangaroo rats and other small rodents these dimensions are extremely well suited for rapid heat exchange. Figure 4 shows a projected tracing of cross
Fig. 3.—Nasal temperatures of kangaroo rats breathing dry air at various ambient temperatures. The temperatures at which the measurements were made are indicated for each group of curves.

sections of the nasal passage of a kangaroo rat at two depths, 3 and 9 mm. The long, narrow configuration provides a large surface area for heat exchange relative to the volume of air passing by. Furthermore, the distance from the center of the air stream to the wall is at no point appreciably in excess of 0.1 mm. Calculations based on these dimensions and on the estimated rate and volume of airflow show that virtually complete temperature and vapor pressure equilibrium can occur between the air and mucosa, even if we assume that the airflow is laminar and heat flow is not facilitated by turbulence.

Discussion.—The extent to which the expired air is cooled prior to its leaving the nose depends on two factors: first, the temperature of the surfaces of the upper res-
The effectiveness of heat transfer in the respiratory tract, and second, the effectiveness by which heat is transferred from the flowing air to these surfaces. The first factor, the temperature of the surfaces, is influenced by the temperature and humidity of the inspired air and by the heat input from the blood perfusing the area. The second factor, the heat exchange between the expired air and the walls of the respiratory tract, will depend on such parameters as the rate of airflow, the temperature gradient between air and wall, type of airflow—whether laminar or turbulent—and the geometry of the respiratory passage.

The nasal tract of man does not acquire temperatures as low as those of the small rodents we have studied. Presumably this is due to the larger dimensions of the passageways which do not allow temperature equilibrium between the core of the air stream and the walls in the short time the air flows over the surface. In addition to the geometry (including a smaller relative surface) differences in blood flow to the mucosa may be of significance. In both the case of the rats and man, however, similar mechanisms of heat and water exchange must operate to establish the temperature gradients found along the nasal passage.

The lowering of nasal temperatures may be regarded as a countercurrent heat exchanger, in principle analogous to biological heat exchangers such as those described, e.g., in the fluke and flippers of whales. In these appendages the blood vessels are arranged so that they can function as heat exchangers when the animals swim in the frigid waters of the Arctic. Each artery is actually surrounded by veins, resulting in a transfer of heat from the arterial to the venous blood, and the latter is thus preheated before it returns to the body. However, while the vascular heat exchanger consists of continuous flow in two tubes separated spatially, the flow in the nasal passages consists of a temporal separation of the flow in a single tube (see Fig. 5).

The intermittent flow in alternate direction permits the removal of heat from the wall during the inward passage of air. Heat is then redeposited during expiration, but complete recovery of heat is limited by the efficiency of the exchanger (and the heat added to the walls from external sources such as blood flow). In dry air the heat removal from the walls is accentuated by evaporation during inspiration; during expiration the cooling removes from the air not only part of the heat, but also part of the evaporated water which is condensed on the cool surfaces as the air temperature decreases. Thus, the countercurrent exchange in the respiratory passages conserves not only heat but water as well.
**Note added in proof:** It has been called to our attention that the heat exchange in the nasal passages was referred to as "countercurrent" heat exchange by J. D. Hardy, *Physiol. Rev.*, **41**, 543 (1961).

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**THE RELATIONSHIP OF THE NUCLEOLUS TO THE SYNTHESIS OF RIBOSOMAL RNA IN HELA CELLS**

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One of the long-standing enigmas of cell biology is the function of the nucleolus. The ease with which the nucleolus may be observed microscopically and its remarkable characteristic of disappearing during mitosis have made it a favorite subject for study; but although much has been said, little has been proved. A recent hypothesis that has received much favorable attention states that the nucleolus is the site of synthesis of ribosomal RNA. It is an hypothesis that rests upon an impressive accumulation of circumstantial evidence, of which the main points are set forth below.

1. Numerous studies with the light microscope have led to the generalization that rapid protein synthesis is correlated with an increase in size of the nucleolus.
2. The nucleolus contains particles that closely resemble, or are indistinguishable from, ribosomes, as observed with the electron microscope. Particles with the sedimentation characteristic of ribosomes may be extracted from isolated nucleoli.
3. The base composition of nucleolar RNA closely resembles that of cytoplasmic ribosomal RNA.
4. Irradiation of nucleoli with an ultraviolet microbeam severely depresses the incorporation of radioactive RNA precursors into nucleoli and cytoplasmic RNA, but has relatively little effect on incorporation into nuclear RNA.
5. Low concentrations of actinomycin D preferentially inhibit incorporation