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INFLUENCE OF THE CAROTID RETE ON BRAIN TEMPERATURE IN CATS EXPOSED TO HOT ENVIRONMENTS

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SUMMARY

1. Thermocouples were chronically implanted in various intracranial and extracranial structures in adult cats. Temperature of arterial blood on the proximal and distal sides of the carotid rete was determined by measuring temperature in the aortic arch and at the anterior cerebral arteries. Temperatures of brain stem regions supplied by the carotid rete and by the vertebral–basilar system were determined by measuring temperature in the anterior hypothalamus and the caudal medulla. Nasal mucosal temperature was measured with a thermocouple implanted in the nasal cavity.

2. In a cool environment (25° C), the temperature of anterior cerebral arterial blood was lower than aortic arterial temperature. Anterior cerebral temperature showed shifts which were not present in central (aortic) arterial blood and which were clearly associated with changes in heat loss from the nasal mucosa and with the behaviour of the animal. When the cats were relaxed or in e.e.g. slow-wave sleep, the nasal mucosal temperature was high and the temperature at the anterior cerebral arteries was as much as 0·30° C less than aortic temperature. During behavioural arousal and paradoxical sleep, the nasal mucosal temperature fell and the anterior cerebral arterial temperature rose toward central arterial temperature. Shifts in hypothalamic temperature followed the changes in anterior cerebral arterial temperature. Medullary temperature was higher than aortic temperature and showed shifts which suggested that blood from the rostral circle of Willis mixed with vertebral blood in the basilar artery.

3. When the ambient temperature was raised to 40–45° C the cooling of cerebral arterial blood and brain increased as the rate of thermal panting increased. Respiratory rate increased tenfold and aortic temperature rose by 2·0–2·5 °C. Anterior cerebral arterial temperature fell below aortic temperature by as much as 1° C, hypothalamic temperature dropping in

parallel with cerebral arterial temperature. Medullary temperature cooled below aortic temperature during heat exposure, but the temperature drop in the medulla was not as high as in the rostral brain stem.

4. Blowing air into the nasal cavity of anaesthetized cats produced a large, rapid temperature drop at the anterior cerebral arteries and in the hypothalamus, with little effect on central arterial temperature. The same experiments in a dead animal cooled the brain after a longer period of time, suggesting that an active process is involved in the brain cooling observed in living animals.

5. It is concluded that the cooling of the rostral cerebral arterial blood and brain which occurs in cats in a cool environment and is accelerated during thermal panting, is a result of countercurrent heat exchange between arterial blood in the carotid rete and venous blood draining the evaporative surfaces of the upper respiratory passages. Such direct brain cooling during thermal panting has now been demonstrated in the cat, the sheep and the gazelle, and probably explains the high heat tolerance of the carnivores and hoofed mammals in which a rete is present.

INTRODUCTION

In mammals, the temperature of the brain is controlled primarily by the temperature of the arterial blood which supplies the brain (Hayward, Smith & Stuart, 1966). The relationship between brain temperature and deep body temperature depends upon the anatomy of the extracerebral arteries supplying the circle of Willis. In the monkey and the rabbit, mammals in which the internal carotid artery runs uninterrupted from the common carotid to the circle of Willis, the temperature of cerebral arterial blood is the same as temperature of blood leaving the heart (Hayward, 1967; Baker & Hayward, 1967*a*; Hayward & Baker, 1968). In these animals, changes in deep body arterial temperature are reflected by similar changes in brain temperature. In the cat and the sheep, where the circle of Willis is supplied by an arterial network called the carotid rete (Davis & Story, 1943; Daniel, Dawes & Prichard, 1953), the temperatures of cerebral arterial blood and brain are different from aortic arterial temperature. This difference is due to a change in temperature of the arterial blood as it flows through the carotid rete (Baker & Hayward, 1967*b*; Baker & Hayward, 1968).

Experiments in hoofed animals suggested that heat exchange in the rete might play an important role in the maintenance of brain temperature during exposure to hot environments. When sheep were exposed to high ambient temperatures, the cerebral arterial blood and brain were cooled as the rate of thermal panting increased, keeping brain temperature low

in the face of a rising central arterial blood temperature (Baker & Hayward, 1968). A similar dissociation between brain temperature and deep body arterial temperature was demonstrated during thermal panting in an African gazelle, another animal in which a carotid rete is present (Taylor 1969). There were reports that brain temperature in the cat remained below rectal temperature during panting (Forster & Ferguson, 1952; Hunter & Adams, 1966), but the data were insufficient to determine whether the carotid rete might play the same role in the panting cat as in the sheep and gazelle. The purpose of the present experiment was to study the role of the carotid rete in control of brain temperature in cats exposed to hot environments.

METHODS

Four adult female cats were used. They were prepared for temperature recording as described previously for the sheep (Baker & Hayward, 1968). The animal was anaesthetized with sodium pentobarbitone (25–30 mg/kg I.P.) and copper-constantan thermocouples were implanted in various intracranial and extracranial locations (Fig. 1). Thermocouples were made from enamelled 100 micra wires with arc-welded junctions about 0·2 mm in diameter. Intracranial thermocouples were cemented to strut wires (0·3 mm diameter) with a thin coat of epoxy resin. They were implanted stereotaxically at the rostral and caudal ends of the brain stem in order to measure temperature of regions supplied by both the carotid rete and the vertebral-basilar system as shown in Fig. 1 (Holmes, Newman & Wolstencroft, 1958; Daniel *et al.* 1953). The rostral probe, with two thermojunctions 6 mm apart on the same strut wire, was pushed through the brain so that the distal junction lay in the basal subarachnoid space next to the anterior cerebral arteries and the proximal junction was in the hypothalamus. Previous studies showed that temperature measured in the basal subarachnoid space near the cerebral arteries is a good index of temperature of arterial blood in the cerebral arteries (Hayward & Baker, 1968). The caudal probe was implanted in the medullary reticular formation a few millimetres dorsal to the basilar artery. In two cats, thermocouples were implanted in the posterior thalamus, in the lateral geniculate bodies or pulvinar.

Central arterial temperature was measured with a thermocouple in polyethylene tubing (o.d. 0·6 mm) implanted in the aortic arch through the common carotid artery. The probe was advanced through a small hole in the wall of the common carotid and cemented to the outside of the arterial wall with a cyanoacrylate adhesive (Bucrylate Tissue Adhesive, Ethicon, Inc., Somerville, New Jersey), fixing it in place and sealing the vessel without occluding the carotid flow. Nasal mucosal temperature was measured with a thermocouple implanted in the nasal cavity on the mucosa. Leads of aortic and nasal thermocouples were threaded subcutaneously to the head and attached to miniature copper-constantan connectors cemented to a lucite skull platform. The platform was elevated above the intact scalp with stainless-steel bolts in the skull (Baker, Burrell, Penkhus & Hayward, 1968). A cortical electroencephalogram (e.e.g.) was monitored between the two parietal bolts which supported the skull platform. A silicone rubber cannula (o.d. 1 mm) was implanted in the right atrium through the external jugular vein for intravenous injections of anaesthetic and its distal end was threaded to the skull platform and capped (Baker *et al.* 1968).

Temperatures and e.e.g. were recorded simultaneously on a Grass Model 6 ink-

writing polygraph. Reference junctions in an ice bath were used and thermopotentials were amplified with chopper-stabilized DC amplifiers. The thermocouples were calibrated before and after each experiment against an accurate mercury thermometer in a constant-temperature bath. The usual sensitivity of this recording system was 0·025° C/mm pen deflexion with an overall accuracy of ± 0·05° C, but in some experiments, preamplifier modules were cascaded to provide a still higher sensitivity.

After a 2-week post-surgery recovery period, each animal was placed in a wire cage (32 in. long × 20 in. high × 22 in. wide) within a temperature-controlled chamber with a one-way glass observation window. Twenty-five control experiments from

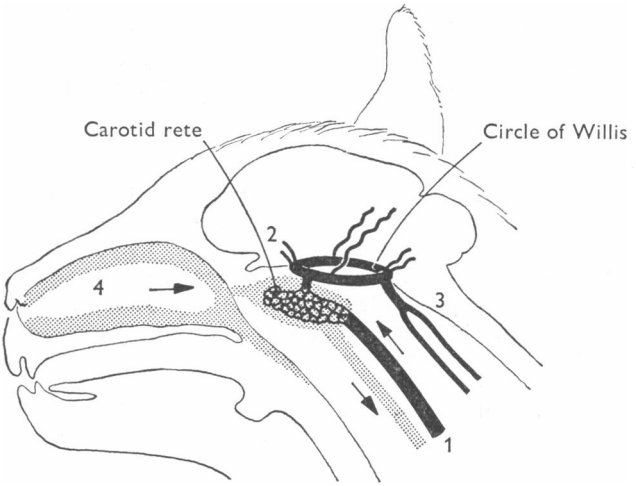

Fig. 1. Schematic sagittal section of the cat head showing the intracranial and extracranial sites at which temperature was measured. The cerebral vascular supply is shown schematically in black. The circle of Willis is supplied anteriorly by the carotid rete and posteriorly by the vertebral arteries. Venous blood (hatched) from the nasal cavity and nasopharynx drains through the pterygoid plexus surrounding the rete and eventually back to the heart. Arrows indicate direction of blood flow. Numbers show sites at which temperature was measured: 1, central arterial temperature, proximal to the carotid rete, in the aortic arch; 2, at the rostral brainstem (carotid rete supply), in the basal subarachnoid space at the anterior cerebral artery and in the hypothalamus a few mm from the anterior cerebral arteries; 3, in the medulla a few mm dorsal to the basilar artery (vertebral–basilar supply); 4, in the nasal cavity, on the nasal mucosa. Note that the actual position of the carotid rete in the cat is extracranial, at the apex of the orbit, and lateral to the midsagittal plane. The rete has been projected onto the midsagittal plane in this Figure for illustration.

1–3 hr long were conducted at an ambient temperature of 25° C. Eighteen experiments were conducted in which the temperature of the recording chamber was raised to 40–45° C and held there for 1–2 hr. The relative humidity in the chamber during these heating experiments varied between 20 and 30 %. In all experiments, the temperatures of central (aortic) arterial blood, cerebral arterial blood, brain and nasal mucosa were recorded, along with the e.e.g. and observations of the animal's behaviour. In the heating experiments, respiratory rates were counted against a

stopwatch. In five experiments, the chronically prepared cats were anaesthetized while temperatures were being recorded and various manipulations of nasal–oral heat loss were made. Each animal was studied for 1–2 months. At the end of the experiments, the locations of the intracranial and extracranial thermocouples were verified by gross dissection and examination.

RESULTS

Brain temperature in a cool environment

Carotid rete supply. In a cool environment (25° C), temperature measured at the anterior cerebral arteries was usually lower than aortic arterial blood temperature. The temperature difference between aortic and anterior cerebral arterial blood was related directly to the temperature of the nasal mucosa. Nasal mucosal temperature showed two distinct types of shifts: small, rapid temperature changes produced by respirations and large, maintained changes in base line temperature associated with the behaviour of the cat (Fig. 2).

When the cats were quietly awake or in e.e.g. slow-wave sleep, the temperature of the nasal mucosa was elevated and the temperature difference between aortic and anterior cerebral arterial blood ranged from 0·10 to 0·30° C. During periods of arousal and of paradoxical sleep, nasal mucosal temperature fell and cerebral arterial blood temperature rose toward the temperature of aortic arterial blood (Fig. 2). The drop in nasal mucosal temperature during arousal or paradoxical sleep was often over 10° C. In an aroused animal, anterior cerebral arterial blood temperature sometimes rose to the same level as aortic arterial temperature for short periods of time, but it never rose above aortic temperature.

Hypothalamic temperature was from 0·15 to 0·25° C above anterior cerebral arterial temperature, the gradient being constant in each animal and depending upon the distance of the hypothalamic thermocouple from the circle of Willis in each cat. Posterior thalamic temperature was from 0·45 to 0·50° C above anterior cerebral temperature. Changes in temperature in the hypothalamus and the thalamus followed changes in the temperature of the cerebral arterial blood (Fig. 2). The gradient of increasing temperature from the cerebral arteries to the centre of the brain has been described previously for the cat (Baker & Hayward, 1967*b*), monkey (Hayward & Baker, 1968), sheep (Baker & Hayward, 1968) rabbit (Baker & Hayward, 1967*a*) and dog (Hayward, 1968), those brain sites farthest from the source of cool blood being warmest. These earlier studies also demonstrated that the temperature gradient between any brain site and the arterial blood which supplies it is constant under all conditions in the normally behaving animal (see hypothalamus and AC–MC in Fig. 2), since

changes in blood temperature are followed by similar changes in brain temperature.

These experiments confirm earlier reports that the arterial blood is cooled as it flows from the aorta to the rostral circle of Willis in the cat (Baker & Hayward, 1967*b*) and they demonstrate that the degree of cooling depends upon heat loss from the upper respiratory passages. Respiratory

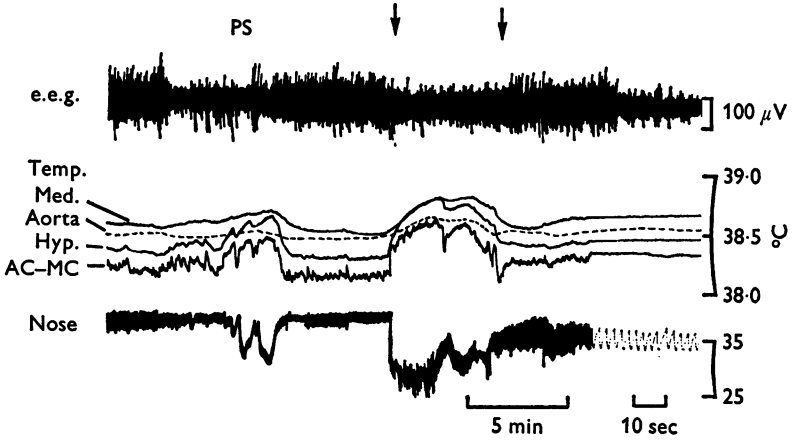

Fig. 2. Brain temperature and respiratory heat loss in the cat in a cool environment. Ambient temperature 25° C. The record shows temperatures of central arterial blood (dashed), cerebral arterial blood, rostral and caudal brain stem and nasal mucosa in a behaving cat isolated in a recording chamber. Cortical electroencephalogram (e.e.g.) is at the top of the Figure. At the beginning of the record, the animal is asleep (slow sleep, high-voltage e.e.g.). During the period marked PS (low voltage e.e.g.), the animal was in paradoxical sleep, after which it dropped into slow sleep again. Between the arrows, the door of the chamber was opened and the cat was handled by the experimenter. Note that when the cat is relaxed or in slow sleep, the nasal mucosal temperature is high and the temperature of the rostral cerebral arterial blood (carotid rete supply) is below aortic arterial temperature. When the animal is aroused or in paradoxical sleep, nasal mucosal temperature falls and cerebral arterial blood and brain temperatures rise. Hypothalamic temperature is higher than the temperature of the arterial blood which perfuses it and changes in hypothalamic temperature are produced by changes in temperature of anterior cerebral arterial blood. Note the constant gradient between hypothalamic temperature and anterior cerebral temperature. Medullary temperature shows shifts which are similar to those occurring in the rostral brainstem, and thus shows a changing relationship to aortic temperature. The nasal mucosa shows large temperature shifts related to the behaviour of the animal and small changes produced by respirations (fast record at right of Figure). Labels: Med., caudal medulla, 3 mm dorsal to basilar artery; Aorta, arterial blood in the aortic arch; Hyp., anterior ventral hypothalamus, 4 mm dorsal to the anterior cerebral arteries; AC–MC, cerebral arterial blood in the rostral basal subarachnoid space, at the junction of the anterior cerebral and middle cerebral arteries; Nose, nasal cavity, on the mucosa.

heat loss is influenced both by the rate of air flow through the respiratory passages and the rate of blood flow through their mucosal surfaces. In a cool environment, the large temperature shifts on the nasal mucosa which are related to behavioural changes in the cat (Fig. 2) are apparently reflexions of changes in mucosal blood flow. Simultaneous measurements of temperature on the nasal mucosa and the skin of the ear in sheep, monkeys and cats (M. A. Baker, unpublished; Hayward & Baker, 1969) showed that the temperature of both sites rose during relaxation and deep sleep and fell during arousal and paradoxical sleep. Since skin temperature is well correlated with skin blood flow in neutral thermal environments (Honda, Carlson & Judy, 1963), the similarity between the behaviour-related temperature shifts on the nasal mucosa and the skin of the ear suggests that both are due to vasomotor activity. Ralston & Kerr (1945) found that in neutral thermal environments, the temperature and the volume of the nasal mucosa in humans were usually positively correlated. In their studies, changes in nasal mucosal temperature were similar to changes in finger skin temperature.

Vertebral-basilar supply. In a cool environment, temperature measured in the ventral caudal medulla, 2–3 mm dorsal to the basilar artery, was higher than aortic arterial blood temperature; but the temperature gradient between the medulla and the aortic arterial blood was variable because the medullary temperature showed shifts which were not present in aortic temperature. Temperature elevations in the medulla occurring during arousal and paradoxical sleep were similar to those in the rostral brain-stem but were smaller and slower (Fig. 2). The presence of independent temperature changes in the medulla and the aortic arterial blood was unexpected, since vertebral blood in the cat does not traverse a rete and since in other animals with functional vertebral arteries, basilar arterial blood temperature is the same as aortic arterial temperature (Baker & Hayward, 1967*a*; Hayward & Baker, 1968; Hayward & Baker, 1969). The similarity between medullary temperature and anterior cerebral arterial temperature suggests that there may be some mixing of blood from the carotid rete supply with vertebral blood in the basilar artery.

Thus, the thermal dissociation between cerebral arterial blood and central arterial blood in the cat is most marked at the rostral circle of Willis and the brain regions supplied by the carotid rete. Temperature in the caudal brain stem seems to reflect primarily the aortic arterial temperature, and it is influenced slightly by the temperature of rostral cerebral arterial blood.

Brain cooling in a hot environment

Eighteen heating experiments were conducted on the four cats. In each experiment, the animal was placed in the wire cage within the environ-

mental chamber and 30 min of control brain and central and cerebral arterial temperatures were recorded at 25° C ambient temperature. Then the air temperature was raised to 40–45° C and held there for 1–2 hr. The heating period lasted from 24 to 30 min (Fig. 3).

In most cases, the animals did not appear to be aware of the rise in chamber temperature until it had reached about 35° C. Then they often became excited and active, pacing about the cage, scratching at the walls

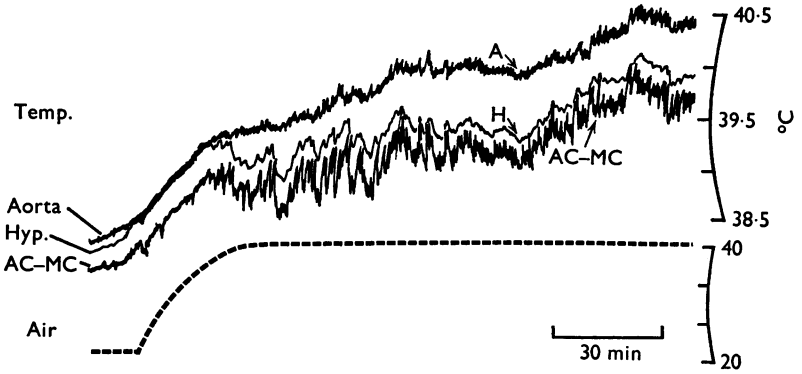

Fig. 3. Brain cooling during heat exposure in the cat. This is a typical record selected from eighteen experiments on four cats. The record shows temperatures of central arterial blood, anterior cerebral arterial blood (carotid rete supply) and brain while the recording chamber was heated from 25 to 41° C and held there for 2 hr. Dashed line shows air temperature. While the chamber was heating, the cat was active and the respiratory rate rose from 20/min to 102/min. Hypothalamic temperature was the same as aortic blood temperature and anterior cerebral arterial temperature was 0·2° C below aortic temperature. The respiratory rate rose to 220/min by 30 min after the chamber temperature had reached 41° C and was 260/min after 60 min at the elevated temperature. Cerebral arterial blood and brain temperatures began to fall below the temperature of aortic arterial blood as the animal spent more and more time lying quietly and panting. The fluctuations in temperature of cerebral arterial blood, reflected with some inertia in the hypothalamus, are related to changes in the behaviour of the animal, peaks occurring when the cat was active and troughs when it was lying quietly and panting. Labels: same as in Fig. 2.

and vocalizing. The time at which panting began was variable, but in most experiments there was a gradual increase in respiratory rate during the time the chamber was heating, from control values of 15–30/min to around 120/min. Open-mouth panting, at rates exceeding 250/min, usually did not begin until after the chamber had reached 40–45° C. At these high ambient temperatures, the animals showed intermittent periods of quiescence and activity which were strikingly correlated with the temperature of the cerebral arterial blood and brain.

Temperatures of aortic arterial blood, anterior cerebral arterial blood and rostral and caudal brain stem rose in parallel during the heating period and continued to rise together as long as the animal was active and excited (Fig. 3). As the period of heat exposure lengthened and the respiratory rate rose, the temperature of the rostral cerebral arterial blood and brain began to drop away from central arterial temperature, cerebral temperatures remaining relatively cool compared to deep body temperature (Fig. 3). Just as in a cool environment, the degree of cooling of the rostral cerebral arterial blood was clearly related to the animal's behaviour and to the respiratory heat loss.

When the cat was active, the temperature of anterior cerebral arterial blood rose toward central arterial temperature. When the animal became quiet and panted with the mouth open, cerebral arterial blood cooled rapidly (Figs. 3 and 4). An active cat which suddenly laid down and began to pant could cool the cerebral arterial blood and brain as much as 1° C in less than 30 sec, with little change in the aortic arterial blood temperature (Fig. 4). Cooling of cerebral arterial blood and brain was maximum when the mouth was open.

In eighteen experiments on four cats, the mean temperature difference between aortic and anterior cerebral arterial blood was $0{\cdot}12 \pm 0{\cdot}02°$ C (mean $\pm$ S.E. of mean) in a cool environment when the animal was relaxed, before heating. Central arterial temperature (aortic) was 38·0–38·5° C. After 1–2 hr in the heat, the aortic arterial temperature had risen to 39·5–40·5° C and the central-cerebral arterial temperature gradient had risen to $0{\cdot}75 \pm 0{\cdot}05°$ C. In three experiments, panting animals cooled the cerebral arterial blood more than 1·0° C below aortic arterial blood temperature. Fig. 5 shows the central-cerebral arterial temperature gradients at increasing levels of deep body temperature during heating.

When the central arterial temperature had risen about 1° C above control levels, the cats began to salivate profusely and to spread the saliva over the chest and forelimbs. This behaviour, which has been described previously in thermally stressed cats (Robinson & Lee, 1942), probably serves to cool the arterial blood supply to the entire body and is not involved in the dissociation of brain and deep body temperature shown in Figs. 3, 4 and 5.

In the heat, just as in a cool environment, the temperature of the brain regions supplied primarily by the vertebral arteries did not dissociate from central arterial temperature as much as the rostral (carotid rete supply) brain regions. However, the temperature of the caudal medulla did become cool, with respect to the aortic temperature, during heat exposure. In a cool environment, the medullary temperature was from 0·15 to 0·30° C higher than aortic temperature. After 1–2 hr in a hot environment, the

medullary temperature was from 0·05 to 0·15° C *lower* than aortic blood temperature. The maximum medullary-aortic temperature gradient change was 0·40° C during one experiment.

There is some cooling of the posterior brain below deep body arterial temperature during heat exposure, but it is small compared to the cooling which occurs in the brain regions supplied by the carotid rete. There are two possible explanations for these observations. First, if a small amount of carotid blood normally flows into the basilar artery, then the cooling of the caudal brainstem could be a result of the increased cooling of arterial blood in the carotid rete during panting. Secondly, there might be a backward shift of the carotid distribution during exposure to heat. Holmes *et al.*

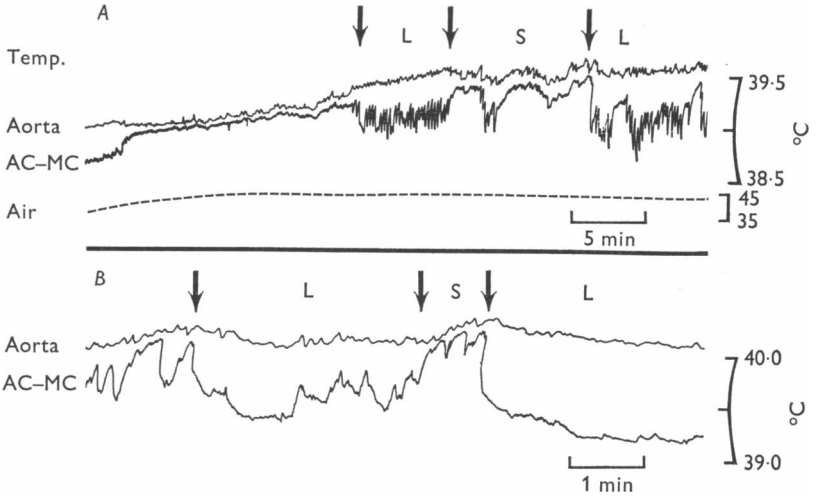

Fig. 4. Influence of behaviour on cooling of cerebral arterial blood during heat exposure in the cat. Part *A* shows central and anterior cerebral arterial blood temperatures during the last part of the heating period and after the chamber temperature (dashed line) reaches 43° C. At the beginning of the record, the animal is lying quietly asleep, and the cerebral arterial blood is 0·30° C cooler than aortic blood. Then the cat wakens and moves around the cage and cerebral arterial temperature rises toward aortic temperature. At the first arrow, the animal lies down and begins to pant with the mouth open, cooling the cerebral arterial blood. At the second arrow, the animal stands and moves around again, and panting is interrupted. During this time, cerebral arterial temperature rises toward aortic temperature. Periods of standing and moving are labelled S and periods of quiet lying and panting are labelled L. Part *B* is a faster-running record from the same experiment, recorded 20 min after the end of the traces shown in Part *A*. Notice the rapidity with which the temperature of the cerebral arterial blood drops when the animal lies down and begins to pant, and the fast rise in cerebral arterial temperature when the animal stands up, all with little change in aortic temperature. Labels: same as in Fig. 2.

(1958), using a dye technique, found that when the carotid blood was heated in anaesthetized cats, the field of supply of the carotid system was enlarged to include the entire basilar artery. If this occurs in cats during exposure to heat, it may represent a means of protecting the entire brain against overheating even though the anatomical substrate for cooling of

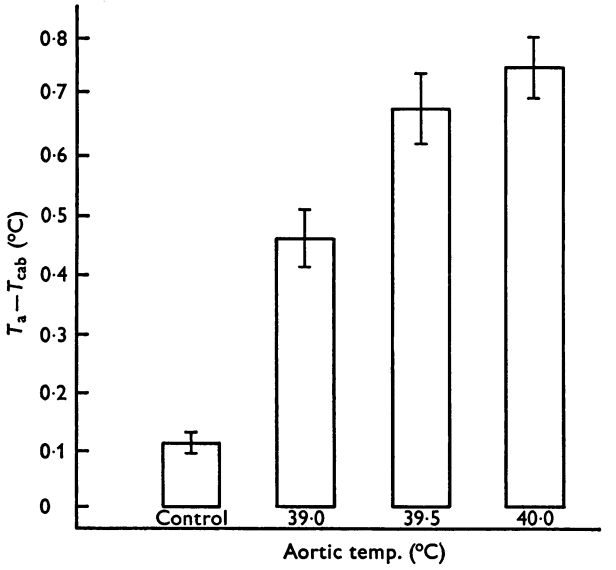

Fig. 5. Progressive cooling of cerebral arterial blood during heat exposure in the cat. Data is averaged from eighteen experiments in four cats. The bars show the mean temperature difference between arterial blood in the aortic arch and rostral cerebral arterial blood (T_a–T_{cab}) at increasing levels of deep body temperature during heating (see Fig. 3 for records of a typical heating experiment). Vertical bars are ± S.E. of means. All gradients were measured when the animals were lying down and, for the higher level of body temperature, panting. When the animals were not lying down and panting at the time that the deep body temperature reached the levels selected for measurements, the measurement was not made. (The small n at 39·0° C aortic temperature reflects the tendency of the animals to be active during the initial part of the heating period, as shown in Fig. 3.) Aortic temperature was between 38·0 and 38·5° C during the control period, when ambient temperature was 25° C. n = 18 for control, n = 7 for 39·0° C aortic temperature, n = 14 for 39·5° C aortic temperature, n = 14 for 40·0° C aortic temperature.

the arterial blood, the carotid rete, is present only in the supply to the rostral. However, the present data do not allow speculation on the distribution of cerebral blood flow during panting, and the answer must await quantitative flow measurements in the carotid rete supply and the vertebral–basilar supply.

Since each cat was exposed to heat on several different occasions, the data were examined to determine whether there was any difference in their responses on subsequent exposures. There was a tendency for the animals to cool the cerebral arterial blood and brain more on later exposures than on earlier ones, but this appeared to reflect a behavioural and not a physiological adaptation. In later heating experiments, most animals were less active and spent more time lying quietly panting, instead of moving around the chamber and vocalizing. The maximal cooling of cerebral arterial blood occurred when the animals were lying down and panting. However, one animal, the most excitable of the four, spent most of the time pacing about or trying to escape from the cage and for that reason showed the least cooling of cerebral arterial blood and brain of any of the cats.

Brain temperature in anaesthesia and during alterations in respiratory heat loss

To study the influence of upper respiratory heat loss on brain temperature under more controlled conditions, the cats were anaesthetized by administering barbiturates, either sodium pentothal or sodium pentobarbitone, 10–15 mg/kg, during a recording session at 25° C ambient temperature. The drugs were injected I.V. from outside the recording chamber through a tube connected to the implanted venous cannula.

A few seconds after the injection, the nasal mucosal temperature rose and the temperatures of the central arterial blood, cerebral arterial blood and brain fell in parallel. The temperature drop was from 0·5 to 1·0° C, the larger drops occurring when more barbiturate was administered. The small temperature fluctuations present in central and cerebral arterial blood and brain of behaving animals disappeared, and these temperatures were steady in the anaesthetized cat.

In thirteen experiments, the nasal evaporative heat loss was increased by blowing air over the nasal mucosa in anaesthetized cats. A respiration pump running at 60 strokes/min and 600 ml./stroke, was connected to a Y-tube with each of its two limbs inserted in one nostril. The onset of the high nasal air flow produced a drop in temperature at the anterior cerebral artery which began within 5 sec and a delayed, smaller temperature drop in central arterial blood (Fig. 6*B*). The drop in anterior cerebral temperature ranged from 0·30 to 1·1° C, with the greater changes produced by longer periods of blowing. Hypothalamic temperature followed cerebral arterial blood temperature with the usual degree of thermal inertia (Fig. 6). The fall in temperature of aortic arterial blood was from one-third to one-half as great as the drop in anterior cerebral temperature. Holding a small block of ice on the roof of the nasopharynx produced a large, rapid temperature drop at the rostral circle of Willis and brain stem, starting within

seconds of the time the ice was placed, and a delayed, smaller drop in central arterial temperature (Fig. 6*A*). During these manipulations of respiratory heat loss, the temperature of the caudal medulla was similar to aortic temperature and did not show the high degree of cooling noted in

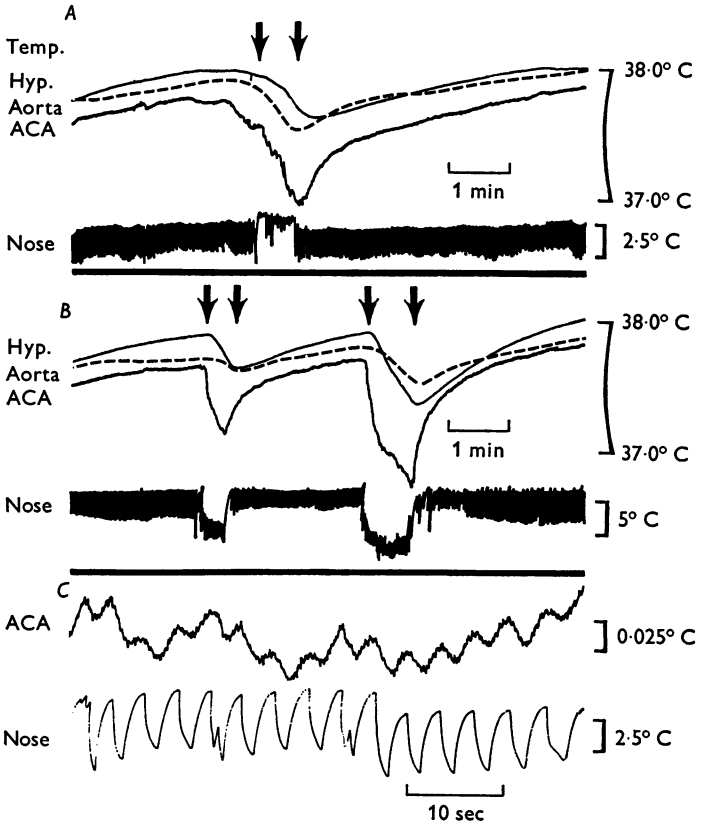

Fig. 6. Brain cooling during high respiratory heat loss in the anaesthetized cat. The records show the temperatures of aortic arterial blood, rostral brain stem and rostral cerebral arterial blood (carotid rete supply) during manipulations of respiratory heat loss in an anaesthetized cat. *A* Between the arrows a small block of ice was placed against the lateral roof of the nasopharynx. The drop in temperature which occurs before the ice was actually in contact with the tissue is probably caused by opening the mouth of the cat and pulling out the tongue. *B* Between the arrows, air was blown into the nostrils through a Y-tube connected to a respiration pump set at 60 strokes/min, 600 ml./stroke. *C* Respiration-related temperature changes measured at the anterior cerebral artery. The gain of the anterior cerebral trace is very high. Inspiration is associated with a drop in cerebral arterial temperature and expiration with a rise.

Labels: same as in Fig. 2, expect ACA is recorded at the anterior cerebral artery rostral to the optic chiasm.

the rostral brain stem. The changes in nasal heat loss produced by respirations were associated with changes in temperature at the anterior cerebral arteries, so small that they could only be seen with high-gain temperature measurements (Fig. 6*C*).

To provide some index of the extent to which the cerebral arterial blood and brain cooling depended upon simple conduction from the base of the brain to the nasopharynx, the experiments were repeated in a dead cat which was in thermal equilibrium with 38° C air in the environmental chamber. When the nasopharynx was moistened with 38° C water and air was blown into it as in the living animal experiments, the temperature of the rostral brain stem eventually dropped, but the drop did not begin until 1 min after the high air flow began. The results with ice were similar, the temperature drop beginning about 50 sec after the ice was placed on the roof of the nasopharynx. Both of these findings contrast sharply with the experiments in living cats and point to some active mechanism being responsible for the rapid transfer of heat from the rostral brainstem to the nasal cavity and nasopharynx.

DISCUSSION

The survival of mammals in the heat depends upon their ability to cool themselves by evaporation of liquid from epithelial surface. In most heat-tolerant mammals, either panting or sweating provides a major avenue of evaporative heat loss, and in some animals both panting and sweating occur in the heat (Schmidt-Nielson, 1964). Until a few years ago, it was assumed that the thermal effects of panting and sweating were essentially the same: namely that cool venous blood leaving the evaporative surfaces returned to the body core and, after mixing with venous blood from other regions, cooled the arterial blood supply to the entire body. More recently, it was shown that panting has an unexpected advantage in some animals, for the arterial blood supply to the brain is cooled below the deep body arterial temperature during panting in the domestic sheep (Baker & Hayward, 1968) and the African gazelle (Taylor, 1969). The present study demonstrates a similar cooling of the cerebral arterial blood in panting cats. Earlier reports that brain temperature was below rectal temperature in panting cats (Forster & Ferguson, 1952; Hunter & Adams, 1966) and dogs (Jackson & Hammel, 1963) were difficult to interpret because it was not known what factors determined the relationship between brain temperature and deep body temperature in mammals.

Hayward and his colleagues (Hayward *et al.* 1966; Hayward, 1967; Hayward & Baker, 1968) showed that in the monkey, the temperature of the arterial blood is the single most important factor controlling brain temperature; and that the temperature of the arterial blood leaving the

heart in the monkey is the same as the temperature of cerebral arterial blood at the circle of Willis, both near the front of the brain and at the basilar artery. Studies in the rabbit confirmed these observations, for cerebral arterial blood in the rabbit is the same temperature as arterial blood in the aorta (Baker & Hayward, 1967*a*). In both the monkey and the rabbit, the circle of Willis is supplied anteriorly by the internal carotid artery and posteriorly by the vertebral arteries (Daniel *et al.* 1953). It was most intriguing to find that in the cat, sheep and dog, the brain-body temperature relationships are much different from those in the monkey and rabbit. In the former, the temperature of cerebral arterial blood is usually less than aortic blood temperature, and cerebral arterial temperature shows large fluctuations not present in aortic blood (Baker & Hayward, 1967*b*; Baker & Hayward, 1968; Hayward, 1968). In cat and sheep, the circle of Willis is supplied anteriorly by the carotid rete, and in the dog by a rudimentary rete (Daniel *et al.* 1953). Simultaneous temperature measurements on the proximal and distal sides of the carotid rete and within the rete itself pointed to the arterial plexus as the site of the changes in arterial blood temperature (Baker & Hayward, 1968).

In these earlier studies it was found that in sheep in a cool environment, heat loss from the nasal passages exerts a powerful influence on the temperature of the carotid rete and of the cerebral arterial blood. When sheep are exposed to heat, the increase in nasal evaporative heat loss during thermal panting cools the blood in the carotid rete over 1·0° C below the temperature of blood leaving the heart (Baker & Hayward, 1968). The present work demonstrates that in the cat, too, nasal evaporative heat loss influences directly the temperature of arterial blood at the rostral circle of Willis and of brain regions supplied by the carotid rete. This relationship between the nose and the cerebral blood supply must account for the brain cooling which occurs during thermal panting.

The nasal mucosa in panting hoofed animals and carnivores possesses several features which make it an ideal site for heat loss. The complex nasal turbinates provide a very large surface which is exposed to respiratory air flow (Scott, 1954). The mucosal coverings of the turbinates and the rest of the nasal cavity are highly vascular and contain a large number of arteriovenous anastomoses (Dawes & Prichard, 1953). Secretions keep the mucosa moist so that evaporation can occur. Schmidt-Nielson, Bretz & Taylor (1970) recently showed that panting dogs tend to inspire through the nose and expire through the mouth. This pattern of air flow is most efficient for nasal heat loss, for it insures that the heat and water vapour lost to the inspired gas is not recovered at the nasal mucosa during expiration.

The heat loss which actually takes place at the nasal mucosa depends not

only upon the rate and pattern of air flow over the nasal passages but also upon the rate of blood flow through the mucosal surfaces. In a cool environment, when the respiratory rate is relatively constant, vasoconstriction of the mucosal vessels decreases the nasal heat loss and vasodilatation increases it. In a warm environment, panting increases the evaporation in the nasal cavity, but vasomotor activity can still influence the heat loss there. Since the carotid rete is surrounded by venous blood draining the nasal mucosa and superficial cranial regions (Davis & Story, 1943; Daniel *et al.* 1953; Baker & Hayward, 1968), the thermal effects of vasomotor activity in the mucosa can be transmitted rapidly to arterial blood in the rete. When the mucosa is constricted, the amount of cool venous blood bathing the rete decreases and cerebral arterial blood temperature rises toward central arterial temperature; when the mucosa is dilated, the amount of cool venous blood bathing the rete increases and blood in the rete is cooled below central arterial temperature.

When Hunter & Adams (1966) observed that hypothalamic temperature in the cat could be cooled below rectal temperature by increasing the rate of airflow over the nasopharynx, they hypothesized that the brain cooling was occurring by direct heat conduction through the tissues between the nasopharynx and the base of the brain. It seems more likely that the mechanism of brain cooling in panting cats is one of vascular countercurrent heat exchange between cerebral arterial blood in the carotid rete and venous blood draining the evaporative surfaces of the respiratory passages. It is clear that dissociation between brain and deep body temperature occurs only in animals with a carotid rete (Hayward & Baker, 1969). The experiments in a dead cat (see Results) showed that transfer of heat from brain to nasopharynx is very slow when conduction is the only available avenue of heat exchange. The possibility that the plexus of arteries forming the rete is cooled conductively through the roof of the nasopharynx during panting cannot be ruled out, but the rapidity with which very small changes in nasal heat loss are transmitted to cerebral arterial blood suggests that the mechanism is one of vascular heat convection.

The presence of a carotid rete in widely differing groups of mammals has led to many speculations about its function. It is now clear that the rete can act to cool the brain during panting in the cat, the sheep and the gazelle. The function of the rete as an arteriovenous heat exchanger may explain its development in heavily furred panting animals with such different habits as the carnivores and the hoofed mammals. Since irreversible changes occur in overheated nervous tissue (Minard & Copman, 1963), it would appear advantageous to expose the cerebral blood supply directly to cool venous blood draining such an efficient evaporative surface as the nasal

mucosa. The presence of a carotid rete may explain the high heat tolerance of the sheep and the cat compared to rats and rabbits and other panting animals with no carotid rete (Robinson & Lee, 1942; Lee, 1950).

Vascular bundles or retes are found in a variety of mammals and birds, usually at the base of the extremities (Scholander & Schevill, 1955). They are efficient arteriovenous heat exchangers and may function in heat-conservation, since they can cool arterial blood flowing into the extremity and thus lower peripheral heat loss at sites distal to the rete itself. When the need for heat dissipation arises, venous blood bypasses the vascular bundles (Scholander & Krog, 1957). However, the thermal role of the carotid rete is basically different from that of these other retes. Situated at the arterial inflow to the heat-sensitive organ, the brain, the carotid rete serves to regulate temperature of arterial blood supplying the brain and thus becomes most important during exposure of the animal to heat stress.

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