Aust. J. Biol. Sci., 1988, **41**, 309–13

Temperature and Humidity of Expired Air of Sheep

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Abstract

The temperature and humidity of expired air from three adult Merino sheep were measured at air temperatures of 20, 30 and 40°C before and after the animals were shorn. Expired air was apparently always saturated with water vapour. At the higher air temperatures the temperature of expired air was close to deep body temperature; at lower air temperatures, expired air had been significantly cooled, e.g. to 32·3°C in shorn sheep at 20°C air temperature. Expired air was cooler from shorn than from unshorn animals at 20 and 30°C air temperature, possibly due to thermally induced vasomotor changes in the upper respiratory tract. Cooling of expired air would be expected to lead to recovery of some of the water evaporated during inspiration; at 20°C air temperature, this fraction was estimated to be 25% in unshorn sheep and 36% in shorn sheep.

Introduction

Air inspired into the lower respiratory tract of mammals comes close to equilibrium with body temperature and to saturation with water vapour (McFadden 1983). During expiration, the temperature of respiratory air decreases as it passes back over surfaces cooled by inspiratory evaporation. The extent of the cooling depends on ambient thermal conditions (Schmidt-Nielsen *et al.* 1970) and the nasal morphology of the animal (Schmid 1976; Langman *et al.* 1979). Cooling of air during expiration leads to condensation of water in the nasal chambers, and thereby to recovery of a fraction of the water evaporated during inspiration. Since the reduction in expired air temperature by this counter-current mechanism determines the extent of water recovery and therefore the respiratory heat loss, it has an important influence on an animal's thermoregulation and water balance (Schmidt-Nielsen *et al.* 1970).

The degree of cooling of expired air in sheep is uncertain. Sheep experience a wider range of effective climatic conditions than most mammals, because shearing drastically alters their microenvironment. After shearing, respiratory variables change and expired air temperatures probably do likewise. Direct measurements of the expired air temperature of sheep have been made (Langman *et al.* 1979), but only at one air temperature and wool length. Some reports allow calculation of expired air temperatures under a range of conditions, but these depend on various untested assumptions (Hofman and Riegle 1977; Hammarlund *et al.* 1986).

The importance of respiration to climatic adaptation and the lack of information about expiratory values in sheep indicate a need to measure the temperature and humidity of expired air of unshorn and shorn animals over a range of air temperatures.

Materials and Methods

Three adult Merino wethers (44–52 kg body weight) were studied over 3 days in June 1986. Wool lengths on the mid-back were 73–83 mm before shearing and approximately 3 mm after shearing.

0004-9417/88/030309$03.00

Before and between experiments, animals were kept indoors at an air temperature (T_a) of 20°C and 10 mm Hg water vapour pressure. Animals were handled according to the Code of Practice for the Care and Use of Animals for Experimental Purposes (NHMRC/CSIRO/AAC).

Respiratory measurements were made in a climatic chamber. Two hours were allowed for the animals to equilibrate to each of the experimental air temperatures of approximately 20°C, 30°C and 40°C, and 10 mm Hg water vapour pressure. After equilibration, measurements took approximately 30 min at each T_a. In each condition, recordings began with measurements of respiratory frequencies from flank movements and of rectal temperatures using a clinical thermometer.

Expired air temperature (T_{exp}) was measured five times on each animal by placing a plastic tube containing a fine thermocouple just inside one nostril, as described by Langman *et al.* (1979). The tube, 9 mm in diameter, had a copper–constantan thermocouple (48 swg, 0·041 mm diameter) fixed at the geometric centre 20 mm from one end. During measurement the thermocouple was held level with the opening of the nostril. The thermocouple output was recorded on a 'Physiograph' (Narco Bio-systems, Houston, Texas) via two amplifiers (Type 7070) in series, which allowed temperatures to be measured rapidly to 0·1°C. The thermocouple reference junction was a Wescor RJ-15 (Wescor Inc., Logan, Utah) and the thermocouple calibration was checked before and after measurements at each T_a. The response time of the system was measured by moving the thermocouple in and out of a stream of warm air. While the tube was in the nostril, T_{exp} fluctuated in phase with respiration, so respiratory frequencies could be counted.

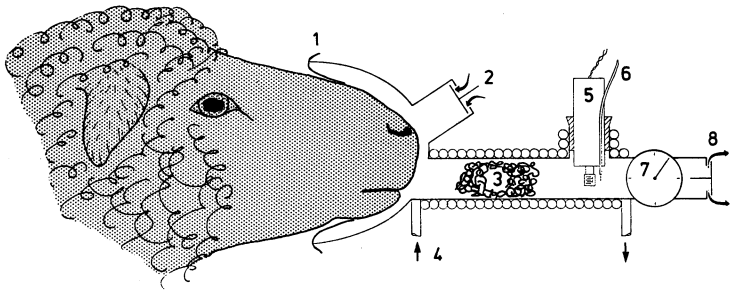

Fig. 1. The system used for measuring humidity of expired air: rubber seal on the mask (1), inlet valve (2), stainless steel wool (3), warm water perfusion (40°C) (4), relative humidity sensor (5), thermocouple (6), respirometer (7), and outlet valve (8).

After these measurements, a special mask was applied to each animal in turn to record simultaneously the expired air humidity, respiratory frequency and respiratory minute volume (R.M.V.). The acrylic mask (Fig. 1) was sealed around the animal's face with a rubber cuff and was held in place by the experimenters during the few minutes of measurement. Room air entered the mask through a spring-loaded, one-way valve. Expired air passed to humidity and temperature sensors via a water-jacketed copper tube, which was heated above body temperature to prevent condensation and which contained stainless steel wool to facilitate mixing and thermal equilibration. The outputs from the relative humidity (r.h.) sensor (Vaisala, Helsinki) and an adjacent thermocouple were measured continuously on potentiometric records, to 1% and 0·1°C respectively. Air was exhaled through a spring-loaded one-way valve, after passing through a Wright respirometer (British Oxygen Company, London) to measure R.M.V. Humidity recordings fluctuated with breathing, allowing measurement of respiratory frequencies while the mask was in place. The response time of the r.h. sensor was not measured, but was reported by the manufacturer to be 'less than 1 sec at 20°C to 90% of final r.h. value'.

After measurements with the mask, the respiratory frequencies and rectal temperatures of the animals were again measured.

Results

Table 1 records the values measured on the three sheep.

Analysis of variance indicated that there was a highly significant difference between

T_{exp} values at different air temperatures ($F = 28{\cdot}4$, 2 and 10 d.f., $P < 0{\cdot}01$) and between unshorn and shorn sheep ($F = 12{\cdot}6$, 1 and 10 d.f., $P < 0{\cdot}01$).

The response time of the thermocouple system for measuring expired air temperature ranged from 40 ms at an air speed of 7 m s^{-1} to 110 ms at 0·8 m s^{-1}.

Table 1. Climatic, body temperature and respiratory values of unshorn and shorn sheep
Values are means ± s.e.m. Number of values in mean in parenthesis

Room air temp. (°C) (2)	Room air r.h. (%) (2)	Rectal temp. (°C) (6)	Resp. freq. (bpm) (12)	Tidal volume (ml) (3)	Exp. air temp. (°C) (3)[A]	Exp. air r.h. (%) (3)[B]
			Unshorn sheep			
20·0	61	39·5±0·1	80±7	245±16	35·3±0·3	100±3
31·5	34	39·2±0·1	86±6	199±25	36·9±0·3	105±6
40·3	23	39·3±0·1	114±6	244±9	38·1±0·3	112±2
			Shorn sheep			
21·3	46	39·2±0·2	32±3	282±28	32·3±1·3	82±7
31·2	26	39·1±0·1	50±6	228±10	34·2±0·8	104±5
38·0	20	39·1±0·1	106±10	200±20	38·5±0·2	100±4

[A] Five values were measured on each animal at each T_a.
[B] Five values were calculated for each animal at each T_a; values exceeded 100% after correction for differences in air temperature at the sensor.

Discussion

The validity of values in Table 1 depends partly on the response times of the measuring systems. The response time of the thermocouple system was such that at all calculated air flow rates, the fine thermocouple reached 99% equilibration during expiration (i.e. expiration was longer than five time-constants). Fast recordings of temperature confirmed that thermal equilibration was virtually complete during each breath. The humidity measurements were less precise, for two reasons. The response time of the humidity sensor was slower, and measured samples of expired air contained a component of 'dead-space' air that came from the mask and not the animal. The first source of error would have resulted in r.h. recordings failing to reach their equilibrated values, and thus to lower readings. The second error, due to addition of drier dead-space air to the sample, would also have reduced r.h. values. Since all measured r.h. values of expired air, except those from shorn sheep at 20°C T_a, were calculated to be 100% (or more), expired air was probably fully saturated, except perhaps in the condition noted. Technical difficulties in measuring rapid changes in r.h. have been reported previously (Schmidt-Nielsen *et al.* 1970); more refined techniques are needed to determine the significance of r.h. values calculated to be over 100% and of the recorded unsaturation of expired air from shorn sheep at the lowest T_a.

One further source of error was the imposition of measuring systems on the animals. Respiratory frequencies were generally depressed by measurement of T_{exp} in unshorn sheep but increased during such measurements in shorn sheep. Use of the face mask, on average, depressed respiratory frequencies slightly in all conditions. The overall effects induced by the measuring procedures were variable and no correction for them was made.

Results in Table 1 can usefully be compared with values derived from Hofman and Riegle (1977) on three Dorset ewes (62 kg) before and after they were shorn of 66 mm of wool (Table 2). Values of rectal temperature and respiratory frequency in Table 2 were recorded directly. Tidal volumes are estimates made by those authors based on certain assumptions.

Values of R.M.V. were derived by us from Hofman and Riegle's data. Values of T_{exp} were also calculated by us from Hofman and Riegle's measurements of respiratory evaporative losses, assuming expired air to be saturated.

The similarity of data in Tables 1 and 2, and their consistency with theoretical expectations, suggest that expired air of sheep is saturated with water vapour and cools below body temperature as ambient temperature falls. The value of T_{exp} of 35·3°C at an air temperature of 24·1°C reported by Langman *et al.* (1979) is in agreement with present results. Apparently, small respiratory evaporative heat losses of sheep in cool conditions (Hales and Brown, 1974) are due not only to low R.M.V., but also to low T_{exp}. Hammarlund *et al.* (1986) deduced that expired air of lambs is cooled below body temperature, proposing also that it is unsaturated; their results could be due simply to cooling. The assumptions of Brockway *et al.* (1965) that sheep expire air at body temperature, and of Stafford-Smith *et al.* (1985) that the r.h. of expired air is 85% appear not to be accurate.

Table 2. Climatic, body temperature and respiratory values of unshorn and shorn sheep as reported by, or calculated from Hofman and Riegle (1977)

Values are means ± s.e.m.

Room air temp. (°C)	Room air r.h. (%)	Rectal temp. (°C)	Resp. freq. (bpm)	Tidal volume (ml)	Calculated exp. air temp. (°C)	Assumed exp. air r.h. (%)
			Unshorn sheep			
25	40	39·7±0·1	189±10	185±3	32·1	100
30	40	40·0±0·2	236±19	187±4	35·4	100
35	40	39·8±0·2	253±18	189±13	37·9	100
40	40	40·2±0·2	272±23	214±23	39·2	100
			Shorn sheep			
25	40	39·1±0·1	25±3	460±26	31·9	100
30	40	39·3±0·1	107±24	232±20	37·0	100
35	40	39·3±0·1	222±22	186±6	36·7	100
40	40	39·7±0·1	249±24	182±2	39·1	100

Circulation of blood through the upper respiratory tract changes with variations in air temperature (Hales *et al.* 1976), partly due to a direct effect of temperature on the blood vessels (McFadden 1983) and partly to centrally induced changes in vasomotor tone (Hayward and Baker 1969; Hales and Iriki 1975). Such alterations in vasomotor tone may explain our observation that expired air was 3°C cooler from shorn sheep than from unshorn sheep exposed to 20°C T_a. Greater cooling of expired air would be expected if blood flow in the upper respiratory mucosa of shorn sheep were reduced. At 20°C T_a, shorn sheep would be below thermoneutrality and likely to be peripherally vasoconstricted; unshorn sheep at the same T_a would be above thermoneutrality and peripherally vasodilated (Blaxter 1962).

Data from Table 1 can be used to calculate water recovery during expiration (Schmidt-Nielsen *et al.* 1970). These show that during expiration unshorn sheep at 20°C T_a condensed about 25% of the water evaporated during inspiration, whereas the same animals when shorn recovered 36% by greater cooling of expired air. These estimates are similar to the value of 24% water recovery at 24°C T_a, reported by Schmidt-Nielsen *et al.* (1970). As T_a increased, water recoveries became smaller and there was less difference due to wool length. At 40°C T_a, recoveries were 5–10%.

Results from these experiments are consistent with the propositions that expired air of sheep is saturated with water vapour, and that a counter-current heat exhange operates in the respiratory passages of sheep as in other mammals, so that expired air becomes cooler

as air temperature becomes cooler. The findings extend our understanding of respiratory cooling in sheep by indicating that the temperature and water content of expired air may be influenced by vasomotor tone in the upper respiratory tract.

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Manuscript received 12 October 1987, revised 16 February 1988, accepted 24 February 1988