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Research Article

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Direct Recordings of the Temperatures in the Tracheobronchial Tree in Normal Man

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ABSTRACT In an effort to determine how far inspired air could penetrate into the respiratory tract before being brought to body conditions, we measured the temperature in the airways of the anterior basilar segment of the right lower lobe in five normal subjects while they breathed air at subfreezing and ambient conditions. During quiet breathing, most of the heating of the incoming gas took place in the upper airways as expected. However, as the thermal burden was increased by rapid inspirations, frigid air, and hyperventilation, the temperature of the distal airways progressively fell and the point at which the incoming air reached body conditions moved deep into the periphery of the lung. These findings demonstrate that heat and water transfer is not localized to one region, but rather is a continuous process that begins the moment the air enters the body and involves as much of the respiratory tract as necessary to complete the task.

INTRODUCTION

During inspiration, it is well accepted that the incoming air is heated and humidified in a coupled fashion, so that by the time the air reaches the alveoli it is fully saturated at body temperatures. The point in the airways at which this process terminates, however, is unknown. In the past it has been generally assumed that the transfer of heat and water from the mucosa is complete, or nearly so, by the time that the inspire reaches the posterior pharynx or upper trachea (1-5). Yet, recent evidence demonstrates that when minute ventilations are elevated, either with exercise or with voluntary hyperventilation, the ability of the upper air passages to condition the air is overcome and the intrathoracic airways begin to participate in the process. In the course of this activity, the temperature

of the airways falls and when the airways become sufficiently cooled, bronchoconstriction develops in both normal and asthmatic individuals (6-12). The severity of the obstruction and its predominant site appear to be related to the magnitude of the temperature change and to the length of airway segment cooled, at least in asthmatics (9-12). Thus, the depth to which incompletely conditioned air can penetrate within the tracheobronchial tree appears to be an important phenomenon with significant clinical implications.

In an effort to obtain more information about where air is finally conditioned, we placed thermocouples in the airways of normal subjects and had them perform various respiratory maneuvers while breathing air at several temperatures. Our observations form the basis of this report.

METHODS

Our subjects consisted of five nonsmoking adult males (mean age = 36 ± 9 yr [SD]) who were trained in the performance of respiratory maneuvers. All had normal pulmonary mechanics and were free of any cardiac or pulmonary disorders. Informed consent was obtained from each participant.

After spraying the nose and throat with a local anesthetic (4% lignocaine), the seated subjects had a flexible fiberoptic bronchoscope (BF-B3 Olympus Optical Co., Tokyo, Japan) inserted through the nasopharynx into the opening of the anterior basilar segment of the right lower lobe. When the tip of the endoscope was in the intended position, a copper constantan thermocouple, ~1 mm in Diam, was threaded through the suction channel and placed into the sub-subsegmental bronchi under direct vision. The distance from the nares to the tip of the thermal probe was recorded, and then the bronchoscope was carefully withdrawn over the thermocouple wire into the subglottic area leaving the probe undisturbed in its original position. When this had been accomplished, the endoscope and the thermocouple within were secured to prevent movement. (The technique used represents a modification of that used at the Lung Function Unit of the Brompton Hospital for the measurement of segmental gas exchange [13], and permitted us to monitor the position of the probe.) The 95% response time of the thermocouple was 0.19 s and was judged adequate for the pur-

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poses of this study. No premedication was given, and the instillation of further lignocaine (2% solution) into the airways during instrumentation was kept to the smallest quantity that effectively prevented cough. Once the probe was in position, its presence was well tolerated even after the anesthesia wore off, which it was permitted to do in four of the five subjects.

With nose clips in place, the subjects then inhaled both subfreezing air and air at ambient room conditions of temperature and humidity while breathing quietly, and while they voluntarily hyperventilated at 30 and 60 liter/min for 4 min each. The sequencing of inspirates was randomly determined. During periods of tidal respiration, maximum inspiratory capacity maneuvers were also obtained with each type of inspirate. In several studies, these maneuvers were also performed as the thermocouple was withdrawn from the lung. The temperature within the airways during inspiration (T_{insp})¹ and expiration (T_{exp}) was continuously measured on a strip chart recorder. At the end of the experiments the position of the probe was verified both visually and by rechecking the distance measurements.

Subfreezing air was produced by having the subjects inspire through a heat exchanger that consisted of a heavily insulated, plastic pipe with a 10-cm i.d. into which a Freon-containing refrigeration coil had been inserted. Room air entered through a large one-way port and was drawn through and around the coil where it could be cooled to values as low as -30°C . The temperature of the air exiting the heat exchanger was continuously recorded by a thermocouple in the air stream on the inspiratory port of the mouthpiece valve. Since room air was used, and since its vapor tension on entering the exchanger had been measured psychrometrically (14), we could then calculate the water content of the air leaving the exchanger from standard tables (14). Both the intrapulmonic and the heat exchanger thermocouples were matched for response times and calibrated using water baths at various temperatures. The calibrations were checked against a precision mercury thermometer and their accuracy was $\pm 0.1^{\circ}\text{C}$. In an effort to determine any potential effects of respiratory secretions, the stability of the thermocouple recording was tested by covering it with films of petroleum jelly and mucous. If the film was thin enough, these interventions were without effect. Thicker films, on the other hand, had a dampening effect on the time constants so that the probe either stopped recording respiratory fluctuations or they were markedly diminished.

During hyperventilation, expired air was directed away from the subjects via a one-way valve into a balloon that was being constantly evacuated at either 30 or 60 liter/min. By having the subjects respire so as to keep the balloon filled, their minute ventilation (\dot{V}_E) could be precisely controlled to match the rate of emptying (8, 9, 11). End tidal carbon dioxide tensions (P_{ETCO_2}) were continuously monitored at the mouth using a Centronic 200 MGA mass spectrometer, (Centronic Medical, Croydon, England) the output of which was displayed on the strip chart recorder. A mixing valve at the inspiration port of the exchanger (or mouthpiece in the room air experiments) permitted the addition of sufficient CO_2 to keep P_{ETCO_2} at resting eucapnic concentrations. As in previous studies employing this approach, P_{ETCO_2} was kept between 37 and 42 Torr (8, 10, 11). Data were analyzed by paired t tests, and one- and two-factor analyses of variance.

¹ *Abbreviations used in this paper:* T_{exp} , temperature within airways during expiration; T_{insp} , temperature within airways during inspiration; \dot{V}_E , ventilation.

RESULTS

The T_{insp} , water contents, and the probe distances are contained in Table I. In the room air experiments, the temperatures and water contents of the inspirates averaged $23 \pm 2^{\circ}\text{C}$ (SD) and 8.5 ± 0.7 mg H_2O /liter, respectively. The mean temperature of the air in the cold experiments was $-17 \pm 2^{\circ}\text{C}$ with a water content of 1.3 ± 0.3 mg H_2O /liter. The tip of the thermocouple was located an average distance of 49 ± 4 cm from the nostrils. Anatomically, this corresponds to the sixth to seventh generation of bronchi.

With the probe in the above position, a single inspiratory capacity of room air was associated with a mean fall in T_{insp} of $0.9 \pm 0.07^{\circ}\text{C}$ (SEM) (Fig. 1). With cold air, the decrease was almost three times as large. Now T_{insp} decreased $2.5 \pm 0.6^{\circ}\text{C}$ from its tidal position. Moving the thermocouple mouthward markedly affected the magnitude of these results (Fig. 2). In one subject when the probe was withdrawn only 8 cm from the anterior basilar segment, T_{insp} fell to 26°C during a maximum inspiration of cold air, and in another individual it was 30°C at the segmental bronchi. Although dramatic, these changes were short-lived and the temperature quickly returned to its base-line expiratory position when the breath was held at total lung capacity for as little as 0.5 s. During spontaneous respiration, however, the temperature changes lasted as long as the particular level of \dot{V}_E was sustained.

The effects of quiet breathing and hyperventilation with room and frigid air with the thermocouple in the anterior basilar segment of the right lower lobe are shown in Figs. 3 and 4. During tidal breathing at ambient conditions, the temperature during inspiration was $0.5 \pm 0.2^{\circ}\text{C}$ lower than that during expiration ($T_{insp} = 36.5 \pm 0.2$; $T_{exp} = 37.0 \pm 0.1^{\circ}\text{C}$; $P = 0.02$) (Fig. 3). Switching to the cold inspirate during quiet breath-

TABLE I
Inspired Air Temperatures and Positions of Intrapulmonic Thermocouple

Subject	Room air		Frigid air		Thermocouple position
	T	WC	T	WC	
TS	24	8.8	-15	1.5	43
AP	22	7.8	-15	1.5	53
BA	22	7.8	-19	1.0	53
DD	25	9.1	-16	1.4	47
RMF	23	9.2	-19	1.0	48
Mean	23	8.5	-17	1.3	49
SD	2	0.7	2	0.3	4

T, temperature of inspirate in $^{\circ}\text{C}$; WC, water content of inspirate in milligrams H_2O per liter of air; thermocouple position in centimeters from the nares.

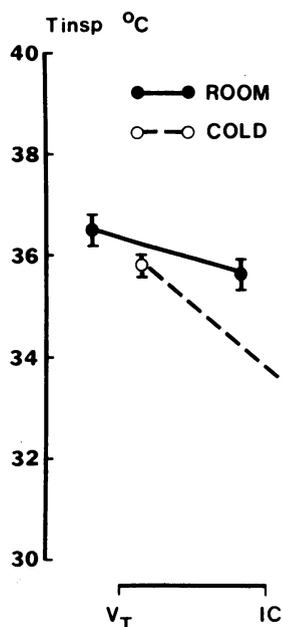


FIGURE 1 Change in T_{insp} during a single maximum inhalation of room and cold air. The data points are mean values and the brackets represent 1 SE. V_T indicates the inspiratory temperature during tidal breathing, and IC represents the fall that occurred at the end of a maximum inspiratory capacity. Comparisons: room, <0.005 ; cold, 0.001 ; room vs. cold, <0.05 .

ing did not materially alter T_{exp} ($36.7 \pm 0.5^\circ\text{C}$), however, T_{insp} fell an average of 1.4°C from its previous value to $35.1 \pm 0.7^\circ\text{C}$ ($P < 0.01$). Increasing \dot{V}_E caused both temperatures to progressively decrease. The

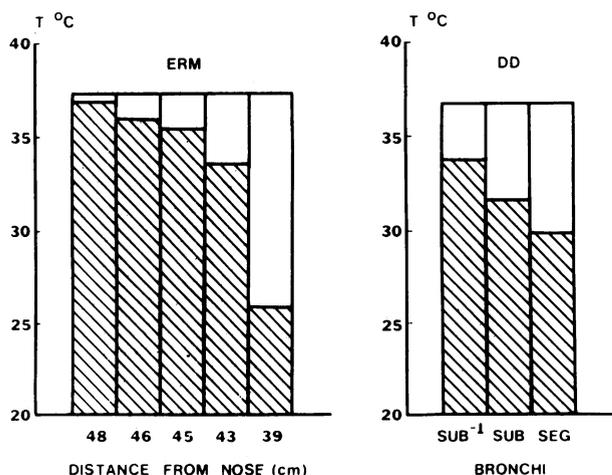


FIGURE 2 Effect of the position of the thermocouple within the airways on the measurement of inspiratory (▨) and expiratory (□) temperatures during maximum inspirations of cold air in two subjects. Sub⁻¹ = sub-subsegmental bronchi; sub = subsegmental bronchi; seg = segmental bronchi.

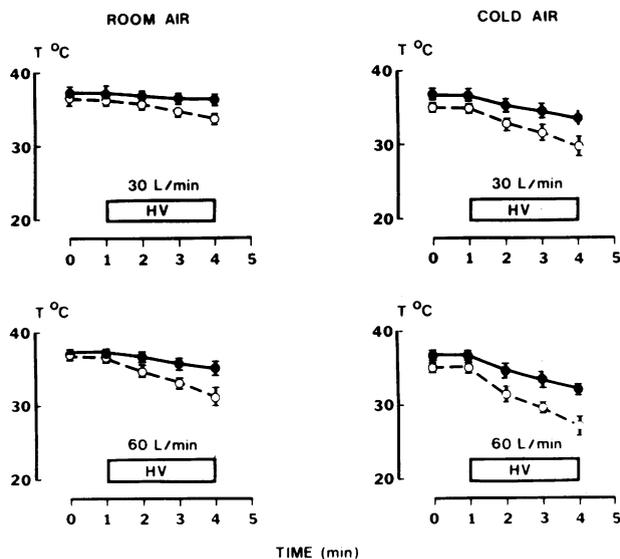


FIGURE 3 Changes in intraairway temperatures during tidal breathing and hyperventilation with room and cold air. The data points are mean values and the brackets represent 1 SE. The rectangles indicate the time spent hyperventilating (HV). T, temperature; ●, expiration; ○, inspiration; L, liters.

higher the ventilation and the colder the air, the greater was the fall.

A comparison of the temperatures in both phases of respiration during the last minute of ventilation under all experimental conditions is contained in Fig. 4. With room air, as \dot{V}_E rose to 30 and then to 60 liter/min, the average T_{exp} decreased 0.9 and 2.1°C from control while T_{insp} fell 2.8 and 5.2°C , respectively. (Each of these changes is significant at the 0.01 level or less.) In absolute terms, at 60 liter/min the mean T_{exp} was 34.9 ± 0.6 and T_{insp} was $31.3 \pm 0.9^\circ\text{C}$. With cold air, these alterations were significantly accentuated. During hyperpnea, T_{exp} and T_{insp} decreased 3.1 and 5.1°C from control, respectively, at 30 liter/min, and 4.1 and 7.6°C at 60 liter/min. During the latter study, the absolute values for T_{exp} and T_{insp} during the last minute of hyperventilation were 32.3 ± 1.0 and $27.3 \pm 1.4^\circ\text{C}$.

The data in Figs. 3 and 4 also indicate that T_{insp} was affected more rapidly and to a greater extent by changes in the level of \dot{V}_E and/or the temperature of the inspire than was T_{exp} . Thus, the mean differences between T_{exp} and T_{insp} grew progressively larger as \dot{V}_E rose, and cold air materially accentuated this effect (Fig. 5).

DISCUSSION

The results of the present study demonstrate that the conditioning of inspired air is a continuous process that begins the moment the air enters the body and involves

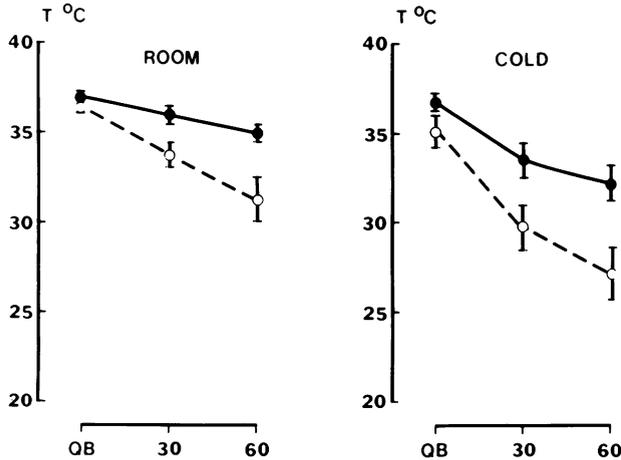


FIGURE 4 Comparison of the temperature (T) in both phases of respiration during the last minutes of quiet breathing (QB), and hyperventilation of 30 and 60 liter/min. The data points are mean values and the brackets represent 1 SE. The data at 30 and 60 liter/min for both temperatures for each inspire are significantly different from their control values and one another at the 0.01 level or less. The cold data for each level of ventilation are significantly different from the room air study at the 0.01 level or less, save for T_{exp} QB. O, inspiration; ●, expiration.

as much of the tracheobronchial tree as necessary to complete the task. Here we show that during quiet breathing with the mouth, most of the heating of the incoming gas (and presumably the humidification) took place proximal to the position of the probe. As the thermal burden was increased, more and more of

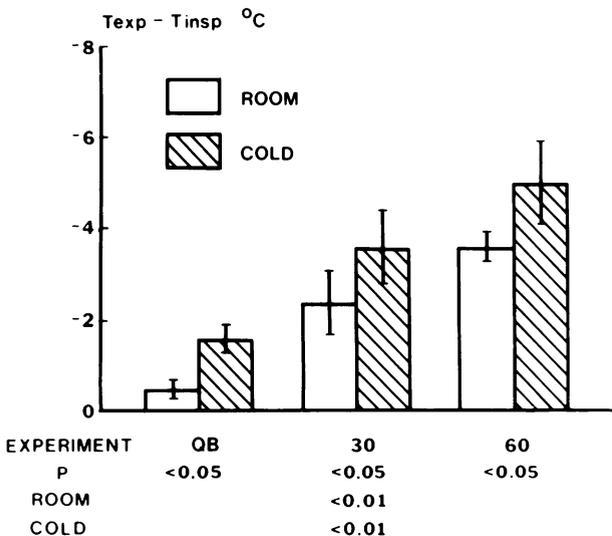


FIGURE 5 Mean differences between expired and inspired temperatures ($T_{exp} - T_{insp}$) during the last minute of quiet breathing and hyperventilation of 30 and 60 L/min for the room and cold air experiments. The heights of the bars represent mean values and the brackets indicate 1 SE.

the tracheobronchial tree became involved, and the point at which the air reached body conditions moved further into the periphery of the lung. This is clearly shown by the inspiratory temperature recordings during the various respiratory maneuvers.

As the heat exchanging capacity of the system was taxed by lowering the temperature of the inspired air, and/or by performing rapid inspiratory capacities and hyperventilation (events that simultaneously incremented the volume of air to be conditioned, but decreased the residence time of the gas by increasing its velocity), T_{insp} progressively fell (Figs. 3 and 4). Since we were recording at a fixed location deep within the lung, the temperature could only have decreased there if less heat had been added to the air before it reached the point of measurement. Therefore, the final modification to body conditions must have taken place at some locale distal to the probe. The exact site at which this occurred is presently unknown, but presumably it was above the respiratory bronchioles and alveolar ducts where air is thought to exist at body conditions (15).

At first glance, the magnitude of the temperature changes we recorded in the right lower lobe seems surprising. Examination of the data in the literature, however, reveals that our observations are compatible with those previously reported. Although a number of authors have measured the temperature of the air within the intrathoracic airways, most of these studies were performed during quiet breathing under usual room conditions (3-5, 15, 16). Even so, the temperatures in the major airways have ranged between 32 and 35°C in the trachea and 34 to 36°C in the main-stem bronchi. In the one study in which ventilation was purposely elevated, T_{insp} was 28 to 29°C, or 6°C less than its value at rest (3). This particular temperature is 2-3°C below that measured in the right lower lobe, and is within the range of what we would have expected had we recorded at a similar site in our study during maximum ventilation on room air. In addition, when consideration is given to the fact that the high heat capacities of the tissues in the trachea and esophagus would have a dampening effect on thermal transmission, the above findings are compatible with the changes reported in retrotracheal esophageal temperatures during exercise and voluntary hyperventilation (9, 10, 17).

Why do peripheral airways participate in heat transfer? Based upon an analysis of the factors that influence the thermodynamics of the lungs, the small bronchi can be thought of as offering a major thermal reserve that can be used as needed. It is known that heat and water move from the mucosa of the airways to the incoming air as a direct function of the temperature and vapor pressure gradients that exist, and

inversely with the linear velocity of the gas and the geometry of the exchanging surface (15). Heating occurs by conduction and convection, but because of the low heat capacity of air, warming is greatly facilitated in structures with large diameters and high air velocities, such as the pharynx and major airways, by turbulent airflow that produces a mixing effect by bringing gas into contact with the exchanging surface (18). Consequently, convection is the principal means of heat transfer in the upper airways, but because of the low surface to volume ratios and high linear velocities found in these areas, the efficiency of heat transfer can be overwhelmed by increasing the volume to be conditioned and/or the flow rates. In the periphery of the lung, however, as the airways branch, linear velocities fall as the total cross-sectional area rises. For example, the 7th and 11th generations of bronchi have 10 and 40 times the surface-area/volume ratios, respectively, than does the trachea and only one-half and one-eighth, respectively, of its linear velocity (19). Consequently, even with very large \dot{V}_E , in the distal small airways progressively slower moving airstreams are exposed to progressively larger surface areas, and there is time for heat to be transferred by conduction. In addition, transitional flow profiles are readily established because of the many bifurcations there (20), and so convection can play a role as well. Since the entire respiratory tract is lined with a fluid surface that is mostly water, the latter can be added at any or all points.

The net effect of the heat transfer during inspiration is to cool the airways so that on expiration the process can reverse along thermal gradients and recovery of heat and water can occur. Thus, at any given point the temperature of the airstream is believed to be the same as that of the airway wall (3, 9, 10, 15). Hence, as T_{insp} falls at a given location, T_{exp} would be expected to follow suit (Figs. 3 and 4). This is an important mechanism for the conservation of water, because as the temperature of the air falls during expiration so does the ability to hold water, and so the latter condenses back onto the mucosa. If the airways were perfect heat exchangers, input would equal recovery, and so T_{exp} would equal T_{insp} at the site of measurement. The data in Fig. 5 indicate that this is not the case. As the need to condition more air arose, concomitant with the movement of the thermal boundary toward the periphery of the lung, the airways became less efficient heat exchangers. Hence, even though T_{exp} fell significantly from its control value, the quantity of heat and water recovered from the alveolus to the point of the probe fell. Unfortunately, measurements were made at only one location and so the overall hysteresis between T_{insp} and T_{exp} along the length of the tracheobronchial tree at rest and under thermal stress remains unknown.

The results of our study potentially could have been modified by several elements in the experimental design. For example, because three-dimensional radiographic techniques were not available to us at the time of this study we had no reliable external means of detecting the position of the tip of the thermocouple. Obviously, if it moved back toward the mouth during hyperventilation, our results would have been incorrect. To ensure that such was not the case, we elected to leave the bronchoscope *in situ*, rather than removing it, so that direct visual inspection of the subsegmental bronchi could be made at intervals throughout the experiments. We also rechecked the measured distances. Consequently, although the precise anatomic location of the tip was unknown, we are certain that no major alteration in its position occurred during the course of any study. (Since the submission of this manuscript, we have subsequently been able to confirm the stability of the position of the probe during hyperventilation directly by observing it with fluoroscopy.)

Because the tip of the thermocouple was not free to move, its position relative to the airways could conceivably have changed as the latter lengthened with inflation and shortened with deflation. The effect that changing airway lengths would have on temperature recordings during quiet breathing and hyperpnea would be expected to be quite small because volume extremes were avoided; however, this phenomenon could possibly have influenced the measurements made during the inspiratory capacity maneuvers. The qualitative pattern would not have been affected, but the magnitude of the decrease in T_{insp} could have been slightly overestimated. As shown in Fig. 2, the airways would have had to elongate 2 cm to have changed T_{insp} substantially.

Similarly, the use of local anesthesia to insert the thermocouple, the position of the bronchoscope in the upper trachea, the size of the thermocouple relative to that of the distal airways, and airway secretions could also have affected our results. However, for a number of reasons we believe it unlikely that any of these factors were significant. First, the duration of anesthesia was short-lived, and in four of our five subjects we made measurements after its effects had clinically dissipated. Second, even if some anesthesia remained, we know from preliminary studies that its effect on temperature is in the opposite direction to what was found here. Lignocaine and its congeners cause the vessels in the respiratory tract to dilate, thus bringing more heat to the surface. (In three subjects, the temperature in the nasopharynx rose an average of 1.3°C after lidocaine; Griffin and McFadden, unpublished observations.) As a consequence, airway cooling is retarded, not facilitated. Third, we tested the possibility of the bronchoscope serving as a heat

sink by removing it in one study. This maneuver did not alter the results in either a quantitative or qualitative fashion. Further, Houdas and colleagues (5) measured the temperatures in the intrathoracic airways through a large rigid metal endoscope and found values that were quite similar to those obtained when only a small wire was inserted directly into the air-stream of the trachea through the crico-thyroid membrane (4). The combination of these findings indicates that instrumentation of the trachea does not carry with it alterations in heat exchange as a matter of course. Fourth, if the thermocouple were to have interfered with regional ventilation for the reasons outlined previously, the low flow rates and small volumes of air associated with partial obstruction would have facilitated local heat transfer. Thus, the falls in T_{insp} and T_{exp} that were recorded would have been smaller than in unobstructed airways and so would have actually underestimated the true situation. With total obstruction, there would not have been any fluctuations in temperature with tidal respiration, T_{insp} would have equalled T_{exp} irrespective of breathing pattern and neither temperature would have decreased with increasing \dot{V}_E and/or inhaling cold air. Fifth, had secretions covered the tip of the thermocouple, based upon our validation experiments we would have expected a marked dampening effect on the recordings, and none occurred.

In summary, the present study presents evidence that demonstrates that the site at which inspired air reached body conditions is not localized to one region of the respiratory tract, but varies with the rate and depth of inspiration. During quiet breathing, the majority of heat and water are transferred in the upper airways. As the need to condition more air arises, especially in association with frigid inspirates, a longer segment of the tracheobronchial tree becomes involved and the thermal boundary moves deep into the periphery of the lung. It is possible that, under extreme circumstances, thermal transfers may continue to take place down the airways to the point at which the air-stream converts from bulk flow to molecular diffusion.

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