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REPORT DOCUMENTATION PAGE		Form Approved OMB No 0704-0188	
AD-A212 060		ELECTE SEP 08 1989 TOB	
1b RESTRICTIVE MARKINGS		DTIC FILE COPY	
3 DISTRIBUTION / AVAILABILITY OF REPORT		Approved for public release; distribution is unlimited.	
5 MONITORING ORGANIZATION REPORT NUMBER(S)		M64-89	
6a. NAME OF PERFORMING ORGANIZATION	6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION	
U.S. Army Rsch Inst of Env Med	SGRD-UE-MEB	U.S. Army Rsch Inst of Env Med	
6c. ADDRESS (City, State, and ZIP Code)		7b. ADDRESS (City, State, and ZIP Code)	
Natick, MA 01760-5007		Natick, MA 01760-5007	
8a. NAME OF FUNDING / SPONSORING ORGANIZATION	8b. OFFICE SYMBOL (If applicable)	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER	
Same as 6a.			
8c. ADDRESS (City, State, and ZIP Code)		10 SOURCE OF FUNDING NUMBERS	
Same as 6c.		PROGRAM ELEMENT NO	PROJECT NO
			3E1627
		TASK NO	87A878
			878/AE
		WORK UNIT ACCESSION NO	084
11 TITLE (Include Security Classification)			
Convective Heat Transfer in Hypobaric Environments			
12. PERSONAL AUTHOR(S)			
Stephen KW. Chang and Richard R. Gonzalez			
13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
	FROM _____ TO _____	July 1989	25
16. SUPPLEMENTARY NOTATION			
17. COSATI CODES		18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)	
FIELD	GROUP	convective heat transfer; hypobaric pressure;	
		heat-mass transfer analogy; Chilton-Colburn j-factor	
19. ABSTRACT (Continue on reverse if necessary and identify by block number)			
<p>→ This study examined the relationship between convective heat transfer and barometric pressure (<math>P_b</math>), specifically, how hypobaric pressure affects the convective heat transfer coefficient (<math>h_c</math>). The U.S. Army Research Institute of Environmental Medicine - High Elevation Simulation Facility was used to simulate five environmental conditions: at elevation of 0 (sea level), 1520m (5000ft), 3050m (10,000ft), 4570m (15,000ft), and 6100m (20,000ft). In the chamber, constant temperature (30°C) and wind speed (0.5m/s) were maintained. The convective heat transfer coefficient was determined using the naphthalene sublimation technique. Circular naphthalene disks were affixed to six sites on a stationary copper manikin. The amount of naphthalene weight loss through sublimation was translated to <math>h_c</math> using the Chilton-Colburn j-factor analogy between heat and mass transfer. As elevation increases, <math>P_b</math> decreases; <math>h_c</math> should decrease accordingly, pointing to a diminished convective heat transfer mechanism. Hitherto, the relationship between <math>h_c</math> and <math>P_b</math> was</p> <p>(continue on reverse)</p>			
20. DISTRIBUTION / AVAILABILITY OF ABSTRACT		21. ABSTRACT SECURITY CLASSIFICATION	
<input checked="" type="checkbox"/> UNCLASSIFIED/UNLIMITED <input checked="" type="checkbox"/> SAME AS RPT <input type="checkbox"/> DTIC USERS		UNCLASSIFIED	
22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code)	22c. OFFICE SYMBOL	
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89 9 06 127

# CONVECTIVE HEAT TRANSFER IN HYPOBARIC ENVIRONMENTS

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Heat exchange between the human body and the environment not only depends on the more familiar factors such as temperature, wind speed and humidity, but also is affected by barometric pressure ( $P_b$ ). The interaction between convective heat transfer coefficient ( $h_c$ ) and  $P_b$  has received little attention, as evident by the limited information available in the literature. While it is known that as elevation increases,  $P_b$  decreases, hence  $h_c$  also decreases resulting in a reduced convective heat transfer process; the exact manner of this dependency is uncertain. This study looked at, both experimentally and theoretically, the relationship between convective heat transfer and barometric pressure, specifically, how hypobaric  $P_b$  affects  $h_c$ .

## METHOD

### Experiment

*A high altitude chamber facility*

The U. S. Army Research Institute of Environmental Medicine (USARIEM) High Elevation Simulation Facility (altitude chamber) was used to simulate five environmental conditions: at sea level (760.0 mmHg), at elevation of 1520 m (5,000 ft, 632.4 mmHg), 3050 m (10,000 ft, 522.8 mmHg), 4570 m (15,000 ft, 429.1 mmHg), and 6100 m (20,000 ft, 349.5 mmHg). For all five environments, the chamber ambient temperature ( $T_a$ ) was maintained at 30°C, relative humidity 20% (dew point  $\approx$ 5°C). This high temperature was necessary to facilitate the naphthalene sublimation process. At 30°C, most human subjects will, to a greater or lesser extent, perspire. Once perspiration occurs, it invariably contaminates the naphthalene, and renders any naphthalene weight measurement useless. To avoid the problem of perspiration contamination, a life-size (1.68 m<sup>2</sup> surface area)

stationary copper manikin was placed in the altitude chamber to model the surface area dimension and the passive dry heat loss of a human subject. Since we were interested only in the convective heat loss, a manikin also eliminated any evaporative contribution generally involved with human subjects. A circular fan aided in regulating the regional air velocity to between 0.4 and 0.6 m/s, depending on different body segments of the manikin. These levels of air velocity (see Table 1) must be maintained throughout all five hypobaric environments.

Circular naphthalene disks were attached to six sites: upper arm, lower arm, thigh, calf, chest, and back, on the manikin. The Figure 1 schematic shows locations of five of the six naphthalene disks. Placement of the back disk mirrored exactly the chest disk. The naphthalene disks (except chest and back disks) were appropriately curved to conform to the corresponding body segment curvature. Airflow was directed normally at the disk surface. Since the naphthalene disk conformed to the body segment curvature and sat directly over the specific body site, the local  $h_c$  over the specific site was measured, rather than an average  $h_c$  for the entire body segment. The regional air velocity and temperature were measured at the six disk sites using an anemometer tree system (TSI Tree System, see Figure 2). The tree system supports six pairs of omnidirectional thermal anemometers (TSI model 1620) and thermistor temperature probes (Yellow Springs Instrument model 705). Each anemometer and thermistor pair was placed approximately 2 cm above and 2 cm away from the naphthalene disk, in such a way as not to disturb the impinging airflow to the disk. The omnidirectional anemometers have a range of 0 - 3 m/s, and a response time of two seconds.

Naphthalene disks were casted using scintillation grade naphthalene. With a melting point of approximately  $80^{\circ}\text{C}$ , the naphthalene was melted and then poured into aluminum disk casting cassettes. The naphthalene quickly hardened at room temperature, after which a nonadhering cover plate was removed to reveal a smooth naphthalene surface. Immediately after casting, the disks were stored individually in airtight containers. All naphthalene disks were allowed to equilibrate in the chamber at  $30^{\circ}\text{C}$  for 24 hours before using. The casting cassettes were appropriately curved to conform to surface curvatures of the upper arm, lower arm, thigh, and calf of the manikin. Cassettes used for the chest and back were flat. For the study, the disks were first mounted into vinyl retainers, which were in turn fastened to the manikin using Velcro straps. The disks were weighed immediately before and after an experiment on a balance sensitive to  $\pm 0.01$  mg. The duration of each experiment was 55 minutes. The naphthalene weight loss, from 55 minutes of sublimation, were translated to  $h_c$  data employing the Chilton-Colburn j-factor analogy between heat and mass transfer [1].

### **Theory: heat-mass transfer analogy and the effect of barometric pressure**

Heat-mass transfer analogy of a sublimation substance has been traditionally used to accurately predict the forced convective heat transfer coefficient [5,10]. Naphthalene very conveniently sublimates at room temperature and thus has been used by a number of investigators to experimentally determine  $h_c$  [2,6,11].

Mass transfer of naphthalene sublimation  $h_m$  can be expressed as [6]

$$h_m = R \cdot T_a \cdot \dot{m} / (P_s - P_a) \quad (1)$$

Assuming the heat of sublimation is negligible,  $P_s$  may be considered as equal to the saturated vapor pressure at  $T_a$  [9],

$$\log_{10} P_s = 11.55 - 3765/T_a$$

or,

$$P_s = 10^{(11.55 - 3765/T_a)} \quad (2)$$

The Chilton-Colburn j-factor analogy [1] can be described:

$$\text{for heat transfer } j_h = \frac{h_c}{\rho \cdot c_p \cdot u} (Pr)^{2/3}, \quad \text{with } Pr = \frac{c_p \cdot \mu}{\kappa} \quad (3)$$

$$\text{for mass transfer } j_m = \frac{P_{AM,n} \cdot h_m}{u} (Sc)^{2/3}, \quad \text{with } Sc = \frac{\mu}{\rho \cdot D_v} \quad (4)$$

Equating heat and mass transfer j-factor,

$$\frac{h_c}{\rho \cdot c_p \cdot u} (Pr)^{2/3} = \frac{P_{AM,n} \cdot h_m}{u} (Sc)^{2/3} \quad (5)$$

$$h_c = \rho \cdot c_p \left( \frac{Sc}{Pr} \right)^{2/3} \cdot P_{AM,n} \cdot h_m \quad (6)$$

$$h_c = (\rho \cdot c_p)^{1/3} \cdot \left(\frac{\kappa}{D_v}\right)^{2/3} \cdot P_{AM,n} \cdot h_m \quad (7)$$

In Equation 7, only  $\rho$  and  $D_v$  are functions of barometric pressure.

$$\text{from [3]} \quad \rho = 1.2929 \cdot \frac{273.15}{T_a} \cdot \frac{P_b}{760.0} \quad \text{kg/m}^3 \quad (8)$$

$$\text{from [6]} \quad D_v = \frac{0.0185}{3600} \cdot \left(\frac{T_a}{273.15}\right)^2 \cdot \frac{760.0}{P_b} \quad \text{m}^2/\text{s} \quad (9)$$

Combining Equations 7 through 9, and substituting in some typical physical properties at 30°C:

$$\kappa = 0.02636 \quad \text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1} \quad D_v = 6.330 \cdot 10^{-6} \quad \text{m}^2/\text{s}$$

$$c_p = 1006 \quad \text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1} \quad \rho = 1.165 \quad \text{kg/m}^3$$

$$\mu = 1.869 \cdot 10^{-5} \quad \text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$$

$$Pr = \frac{c_p \cdot \mu}{\kappa} = 0.7133$$

$$Sc = \frac{\mu}{\rho \cdot D_v} = 2.534$$

$$P_{AM,n} = 0.319$$

Thus,

$$h_c = 1035.7 \cdot \left(\frac{273.15}{T_a}\right)^{5/3} \cdot \left(\frac{P_b}{760.0}\right) \cdot h_m \quad (10)$$

The relationship between  $h_c$  and  $P_b$ , previously has been considered as a nonlinear power function. Gagge and Nishi [4] proposed by rational analogy that barometric pressure should change  $h_c$  by a factor of  $(P_b/760)^{0.55}$ , with  $P_b$  expressed in units of mmHg. The above theoretical derivation of Equation 10 very clearly shows that  $h_c$  varies linearly with  $(P_b/760)$ , rather than as a power function. This study also seeks to corroborate this linear relationship finding with experimental data.

## RESULTS

Table 1 gives the regional air velocity ( $\pm$  dispersion range) at the six naphthalene disk locations: upper arm, lower arm, thigh, calf, chest, and back, on the stationary manikin at sea level setting. Figure 3 shows the local air velocity at the six naphthalene disk sites, at the five  $P_b$ : 760.0, 632.4, 522.8, 429.1, and 349.1 mmHg.

Figure 4 gives the local  $h_c$  at the six naphthalene disk sites, at the five altitudes. The  $h_c$  was computed using Equation 10. For each experimental run,  $h_c$  was averaged over the 55 minute experiment period. The results in Figure 4 are the average of 19 runs. A more detailed set of the data presented in Figure 4 is tabulated in Table 2, where  $h_c$  is shown with its corresponding standard deviation value. Figure 5 shows the same information as Figure 4 in line plots, to accentuate the linear characteristics.

Analysis of variance (ANOVA) was performed on the  $h_c$  values at each disk site, to see if the observed difference was indeed statistically significant. The  $f$ -values from the ANOVA tests are listed in Table 3. A  $f$ -value  $> 2.47$  indicates

that the  $h_c$  sequence does show a significant difference, with  $p < 0.05$ . The Tukey test was then used to determine exactly where the differences lie, and the results are given in Table 4.

The Tukey test was evaluated between  $h_c$  at each adjacent elevations. The 0-1, 1-3, 3-4, and 4-6 columns give the test comparison between elevations of 0 and 1520m, 1520m and 3050m, 3050m and 4570m, and 4570m and 6100m, respectively. From the results of the Tukey test in Table 4, for each disk site the difference-between-means are greater than the respective critical-difference-value, indicating that the  $h_c$  decrements between adjacent elevation levels are all highly significant ( $p < 0.05$ ).

## DISCUSSION

The sea level regional air velocities at the six disk sites, as shown in Table 1, represent the base line air velocity level which must be maintained throughout all five hypobaric environments. Unless constant air velocity is maintained, comparisons of  $h_c$  from the five environments become meaningless. In our study, a circular fan was used to aid in achieving this base line air velocity level since the present altitude chamber does not stringently monitor the chamber airflow. The ranges of the regional air velocities are displayed in Figure 4 with air velocity (in m/s) on the ordinate, and  $P_b$  (in mmHg) as the abscissa. Data for all six disk locations are presented together because all six sets of data display one single result: constant air velocities were maintained throughout the five environments. In Figure 4, at each of the six disk sites, bars of equal height signify that constant regional wind speed was indeed maintained for all five elevations. Again, constant

regional air velocities ensure meaningful comparison of convective heat transfer coefficient  $h_c$  data.

The six  $h_c$  bar graphs in Figure 5 were plotted with  $h_c$  (in  $W \cdot m^{-2} \cdot ^\circ C^{-1}$ ) on the ordinate, and again  $P_b$  (in mmHg) as the abscissa. Again, all six graphs are presented together to highlight one single thesis:  $h_c$  decreased steadily as the barometric pressure decreased from 760 mmHg to 349.5 mmHg. The decreasing trend of  $h_c$  was in fact a linear one. This is accentuated in Figure 6 where instead of bar graphs,  $h_c$  were plotted as line graphs. In all cases, the decreasing trend of  $h_c$  followed a straight line. To further ascertain that the observed linear relationship indeed exists between  $P_b$  and  $h_c$ , a regression analysis was performed using the complete  $h_c$  data set of Table 2. Table 5 gives the results of the regression analysis. For all six disk sites, a linear equation best describes the data with correlation  $>0.99$ . The conclusion must be that  $h_c$  and  $P_b$  exhibit a linear relationship.

The nonlinear power function dependency concept appears to be a residual influence dating from human calorimetric studies of  $h_c$  and air velocity, where  $h_c$  has been shown to vary as a power function of air velocity [6,7,8]. Most likely, realizing that  $h_c$  should vary with  $P_b$ , and as a reasonable approximation the power function idea was adopted. The data in Figures 4 and 5, the theoretical derivation of  $h_c$  in Equation 10, and the linear regression analysis results in Table 5, very clearly demonstrated this power function concept to be groundless and indeed the valid approach is that  $h_c$  and  $P_b$  exhibit a linear dependency.

The implication of the above results is that at a given hypobaric environment, the convective heat transfer mechanism becomes even more restricted, particularly for human dry heat exchange, than was previously thought. As an example, consider  $h_c$  at an elevation of 4570 m ( $P_b = 429.1$  mmHg), and for simplicity assume all other factors, e.g. temperature, humidity, remain constant. From

$$\begin{array}{l} \text{a power} \\ \text{function :} \\ \text{relationship} \end{array} \left( \frac{P_b}{760.0} \right)^{0.55} = \left( \frac{429.1}{760.0} \right)^{0.55} = 73.0\% \text{ of sea level } h_c ;$$

$$\text{a linear relationship: } \left( \frac{P_b}{760.0} \right) = \left( \frac{429.1}{760.0} \right) = 56.5\% \text{ of sea level } h_c .$$

The power function overestimation of  $h_c$  in this example is 16.5%, i.e. the convective heat loss is 16.5% less than previously believed. This overestimation of  $h_c$  becomes more pronounced as the altitude increases.

When the results of this study are applied to human clothing thermal resistance properties, it appears that at higher elevations, the intrinsic insulation property of a multilayered cold weather clothing system could well be underestimated because convective heat loss is lower than previously proposed. Hence, for example, by dressing according to the original conventional nonlinear power function prediction, an exercising person may well be overdressed and suffer from too much heat storage rather than from the inherent cold of high altitude.

Equation 10 applies implicitly also to hyperbaric conditions although no specific hyperbaric data are presented in this report. At hyperbaric  $P_b$ , it can be reasoned that  $h_c$  would be generally underestimated using the invalid power function assumption. Such underestimation could have rather significant consequences, since in a hyperbaric environment, convection becomes the one dominant heat transfer mechanism [12].

**APPENDIX****Symbols and Terminology**

$c_p$  = specific heat ( $J \cdot kg^{-1} \cdot K^{-1}$ )

$D_v$  = mass diffusivity ( $m^2/s$ )

$h_c$  = convective heat transfer coefficient ( $W \cdot m^{-2} \cdot K^{-1}$ )

$h_m$  = naphthalene mass transfer coefficient (m/s)

$j_h$  = Chilton-Colburn analogy j-factor for heat transfer

$j_m$  = Chilton-Colburn analogy j-factor for mass transfer

$\dot{m}$  = naphthalene sublimation weight loss rate ( $kg \cdot m^{-2} \cdot s^{-1}$ )

$P_a$  = naphthalene vapor pressure in air (assumed = 0)

$P_b$  = barometric pressure (Torr or mmHg, 1 mmHg = 133.3 Pascal)

$P_{AM,n}$  = logarithmic mean density factor for naphthalene sublimating in air (ND)

Pr = Prandtl's number (nondimensional)

$P_s$  = naphthalene surface vapor pressure (Torr or mmHg, 1 mmHg = 133.3 Pascal)

R = naphthalene gas constant ( $0.487 \text{ mmHg} \cdot m^3 \cdot kg^{-1} \cdot K^{-1}$ )

Sc = Schmidt's number (nondimensional)

$T_a$  = ambient temperature ( $^{\circ}K$ )

u = air velocity (m)

$\kappa$  = thermal conductivity ( $W \cdot m^{-1} \cdot K^{-1}$ )

$\mu$  = viscosity ( $kg \cdot m^{-1} \cdot s^{-1}$ )

$\rho$  = density ( $kg/m^3$ )

**ACKNOWLEDGMENTS**

We are grateful to the USARIEM Altitude Division, A. Cymerman, Director, for allotted us chamber time, and to G. Iwanyk, Flight Surgeon, for his assistance. We especially thank Messrs. James Devine, Edward Powers, and many others of the altitude chamber operating crew.

The views, opinions, and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other official documentation.

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Table 1 Regional air velocity on the stationary manikin, at sea level

naphthalene disk site	regional air velocity (m/s)
Upper Arm	0.538 ± 0.025
Lower Arm	0.576 ± 0.007
Thigh	0.690 ± 0.019
Calf	0.649 ± 0.043
Chest	0.395 ± 0.033
Back	0.231 ± 0.013

---

air velocity data represent as Means ± SD

Table 2 Regional  $h_c$  at 760.0, 632.4, 522.8, 429.1, and 349.5 mmHg

	760.0 mmHg (0 m)	632.4 mmHg (1520 m)	522.8 mmHg (3050 m)	429.1 mmHg (4570 m)	349.5 mmHg (6100 m)
Upper Arm	6.79±0.319	5.27±0.260	4.08±0.199	3.19±0.127	2.46±0.137
Lower Arm	7.37±0.262	5.88±0.279	4.61±0.198	3.66±0.139	2.87±0.154
Thigh	7.45±0.324	6.05±0.321	4.85±0.161	3.94±0.169	3.06±0.140
Calf	7.38±0.394	6.06±0.428	4.96±0.186	4.27±0.290	3.26±0.117
Chest	5.76±0.260	4.37±0.254	3.36±0.183	2.61±0.107	1.99±0.130
Back	3.64±0.283	2.69±0.243	2.08±0.142	1.69±0.127	1.29±0.092

---

$h_c$  data represent as Means  $\pm$  SD; unit of  $h_c$  is  $W/(m^2 \cdot ^\circ C)$

Table 3 *f*-value from Analysis of Variance (ANOVA test)

	Upper Arm	Lower Arm	Thigh	Calf	Chest	Back
<i>f</i>	1088.62	1190.62	956.93	485.65	1029.73	414.36

---

A  $f > 2.47$  indicates that significant difference exists ( $p < 0.05$ )

Table 4 Tukey test results

	Difference Between Means				Critical Difference Value
	0 - 1	1 - 3	3 - 4	4 - 6	
Upper Arm	1.520	1.195	0.886	0.730	0.195
Lower Arm	1.497	1.263	0.953	0.795	0.194
Thigh	1.403	1.202	0.912	0.874	0.209
Calf	1.318	1.101	0.688	1.011	0.271
Chest	1.386	1.008	0.758	0.615	0.174
Back	0.947	0.610	0.398	0.392	0.169

column 0-1 compares data between 0 and 1520m elevations  
 column 1-3 compares data between 1520m and 3050m elevations  
 column 3-4 compares data between 3050m and 4570m elevations  
 column 4-6 compares data between 4570m and 6100m elevations

Difference is statistically significant ( $p < 0.05$ ) when the  
 Difference-Between-Means is greater than the Critical-Difference-Value

Table 5 Linear regression equation between  $h_c$  and  $P_b$ 

disk site	linear equation from regression analysis	correlation ( $p < 0.0005$ )
Upper Arm	$y = 0.01054 x - 1.32$	$r = 0.998$
Lower Arm	$y = 0.01100 x - 1.05$	$r = 0.999$
Thigh	$y = 0.01065 x - 0.67$	$r = 0.999$
Calf	$y = 0.00979 x - 0.09$	$r = 0.998$
Chest	$y = 0.00914 x - 1.30$	$r = 0.997$
Back	$y = 0.00562 x - 0.75$	$r = 0.994$

In the resulting linear equation  $y = mx + b$ :  
 $y = h_c$  data in  $W/(m^2 \cdot ^\circ C)$  (as dependent variable)  
 $x = P_b$  in mmHg (as independent variable)  
 $m =$  slope of straight line  
 $b =$  constant (intercept value on the ordinate axis)

**Figure legends**

Figure 1 Schematic of manikin showing locations of the naphthalene disks

Figure 2 Anemometer tree

Figure 3 Regional air velocities

Figure 4 Local  $h_c$  data

Figure 5 Local  $h_c$  data as line plots

Figure 1

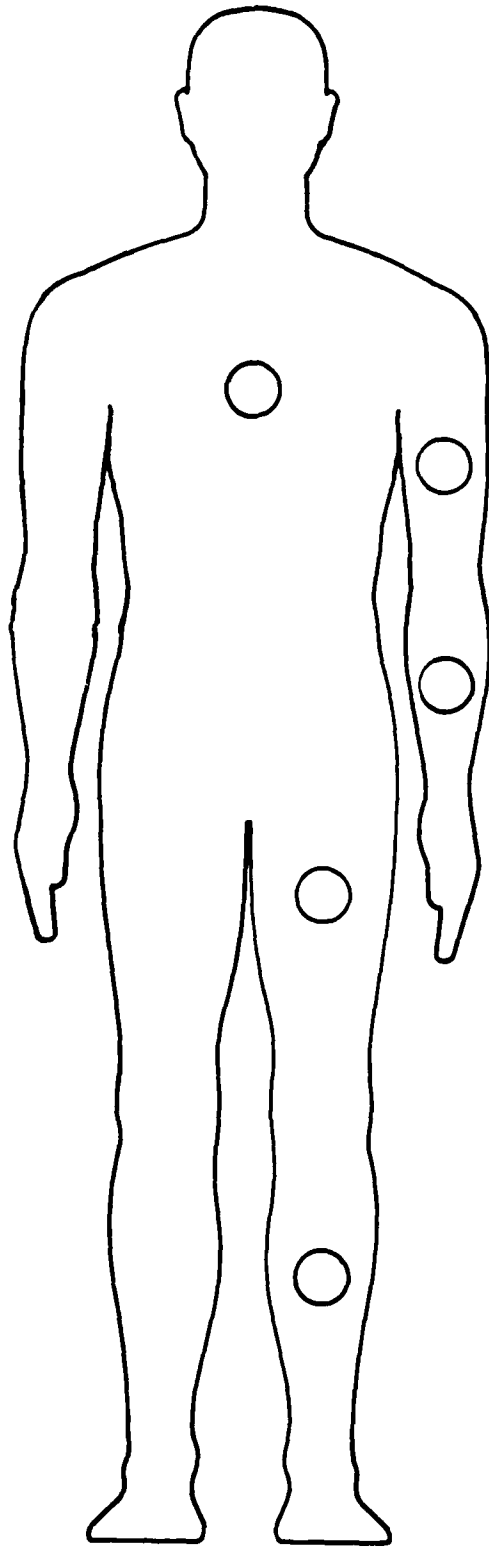
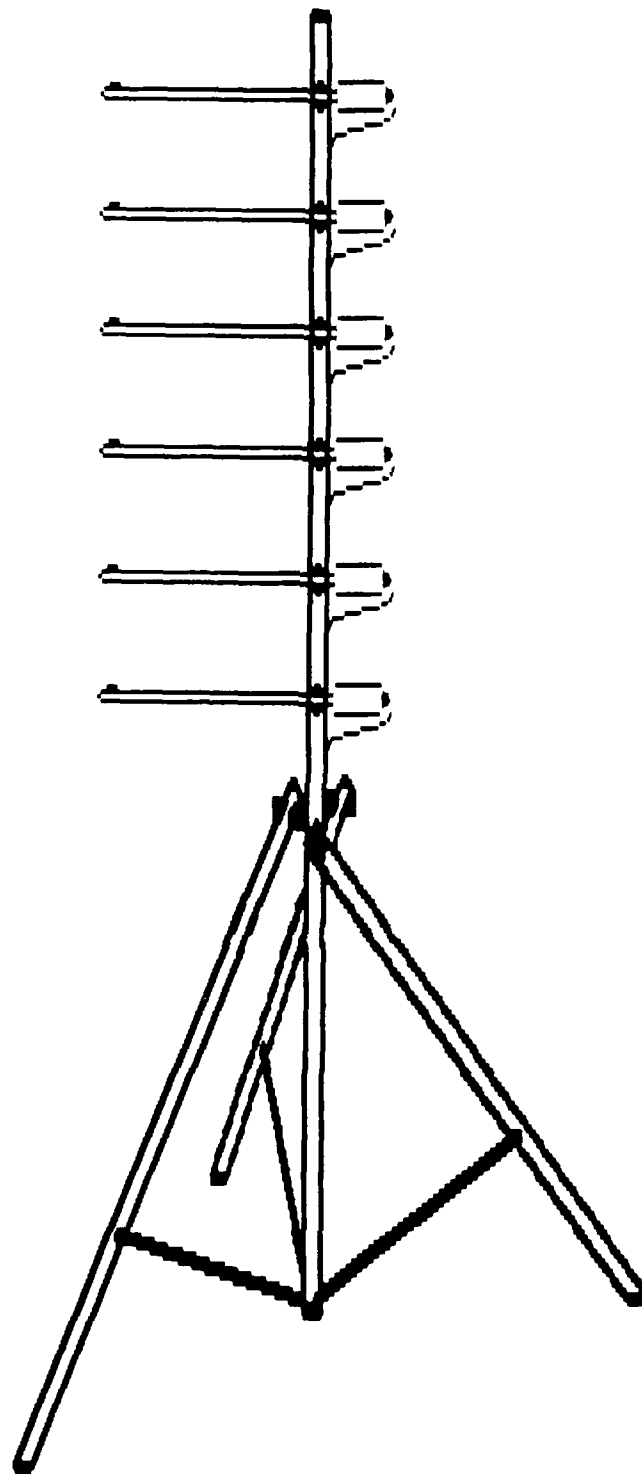
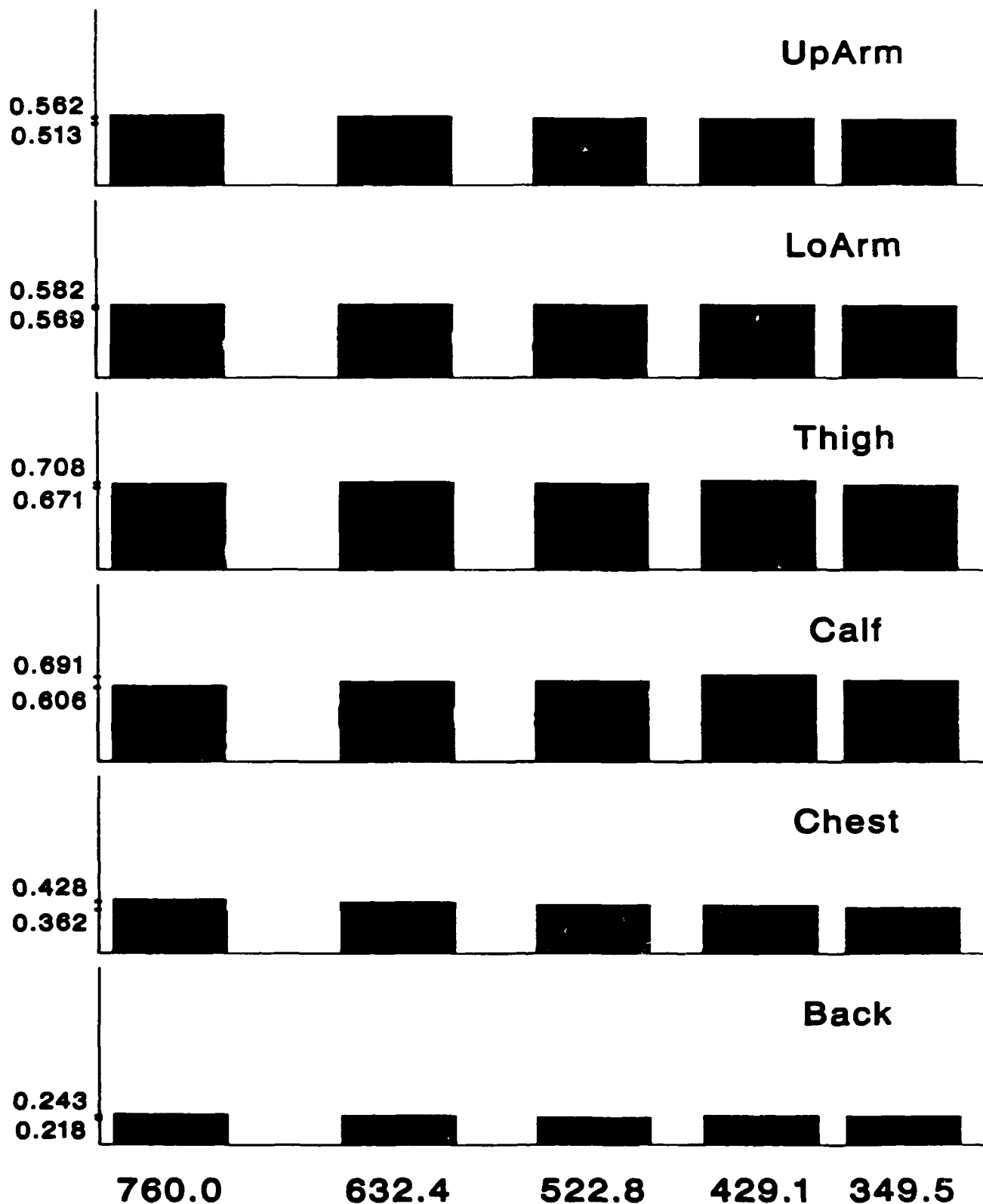


Figure 2

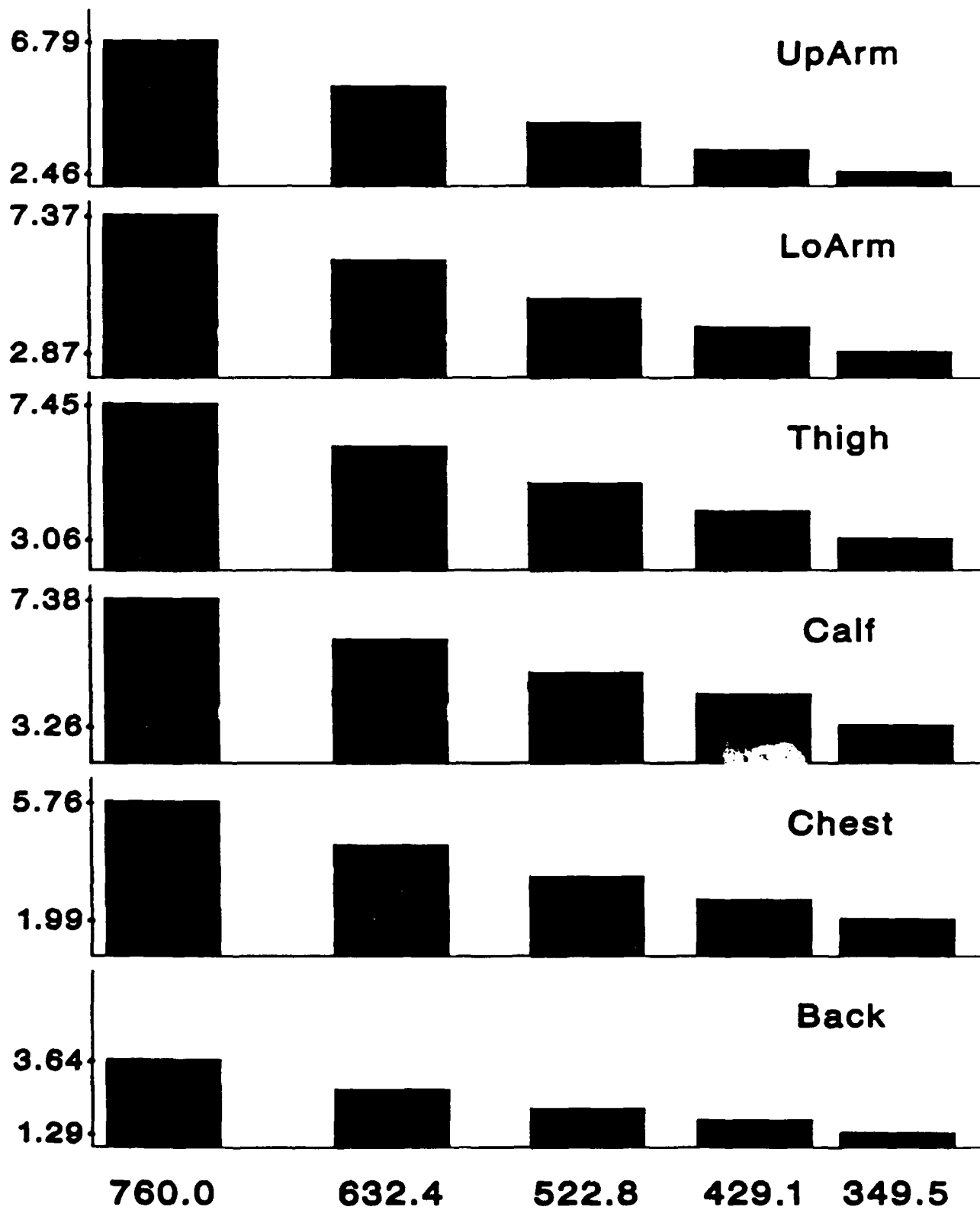


# Figure 3

# Air Velocity



# Figure 4 Hypobaric $h_c$



# Figure 5 Hypobaric $h_c$

