INTRODUCTION

Does endurance training alter the mechanical properties of the respiratory system (i.e. the physical forces which oppose the displacement of the respiratory system during pulmonary ventilation)? There is a paucity of data relevant to this question in the literature, but such information would provide a better understanding of the training-related changes which have been observed in several respiratory mechanics parameters such as the maximum breathing capacity. Such data may also provide a better understanding of the means by which training can improve exercise endurance because of the high oxygen cost of breathing during strenuous exercise. A training-related decrease in the respiratory resistances would decrease the work and oxygen cost of breathing and thereby improve endurance. Such an effect may contribute to the training-related increases frequently observed in the mechanical efficiency of exercise (i.e. the useful mechanical work performed to total energy expended during exercise). This thesis reports a study which examined the role of endurance training on the total mechanical work of breathing and the extent to which any changes therein would contribute to an improvement in exercise endurance.

The respiratory mechanics symbols used in this report are based on the nomenclature by Mead and Milic-Emili (1964). A glossary of the more commonly used symbols is provided in Appendix 1.

CHAPTER 1

RESPIRATORY MECHANICS AND THE WORK OF BREATHING

INTRODUCTION

Pulmonary ventilation requires the performance of work by the respiratory muscles to overcome several types of resistive forces which oppose the movement of air along the airways and the displacement of the lungs and thoracic structures. The phrase "thoracic structures" is used here to mean all the structures surrounding the lungs which are displaced during respiratory movements. These include the chest wall, diaphragm, the organs of the mediastinum, and the abdominal contents. The phrase "total respiratory system" refers to all the structures displaced during respiratory movements (i.e. the lungs and thoracic structures). The material presented in this Chapter apply to healthy adult humans unless otherwise specified.

THE RESPIRATORY RESISTANCES

Elastic Resistances

Elastic resistances, or elastances, oppose the displacement of the tissues of the lungs and thoracic structures (Otis, Fenn and Rahn, 1950), where the elastance of the total respiratory system (E_r) equals the sum of the elastances of the lungs (E_l) and thoracic structures (E_w). The magnitude of these resistances vary with the lung volume in humans and other mammals, but are relatively constant over the eupnoeic lung volume range where E_r is lowest (Agostoni, Thimm and Fenn, 1959; Drorbaugh, 1960; Agostoni and Mead, 1964). A more detailed appreciation of the relationship between the elastances and lung volume can be obtained by examining the static pressure-volume (P-V) curves of the total respiratory system and its components from these studies.

Dynamic Resistances

The total dynamic resistance of the respiratory system (R_r) is defined as the pressure required to overcome all the dynamic forces opposing respiratory movements (P_{dyn}) per unit of airflow ($\dot{V}$), and

contains both viscous and nonviscous components (Otis, Fenn and Rahn, 1950; Mead and Agostoni, 1964). The pressure required to overcome R_r is related to $\dot{V}$ as described in equation 1.

$$P_{dyn} = K'\dot{V} + K''\dot{V}^2 \quad (1)$$

where K' and K'' respectively represent the viscance and dynamic nonviscous resistance of the total respiratory system (Otis, Fenn and Rahn, 1950). The term viscance is synonymous with viscous resistance.

The R_r equals the sum of the airway resistance (R_{aw}) and the dynamic resistance of the total respiratory system tissues (R_{rt}). The latter component has lung and thoracic structures components (R_{lt} and R_w respectively), and the pulmonary flow resistance (R_l) equals the sum of R_{aw} and R_{lt}.

The dynamic respiratory resistances have both viscous and nonviscous components (Otis, Fenn and Rahn, 1950; McIlroy, Marshall and Christie, 1954; Mead and Agostoni, 1964). The viscous component of R_{aw} represents the flow resistance due to laminar airflow, whereas the dynamic nonviscous component results from turbulent airflow (Otis, Fenn and Rahn, 1950; Mead and Agostoni, 1964). As the dynamic respiratory resistances are comprised of both viscous and nonviscous components, a given increase in airflow will require a greater increase in the driving pressure. The dynamic respiratory resistances consequently rise as the airflow increases (Mead and Whittenberger, 1953; Fry *et al.*, 1954; Mead and Agostoni, 1964).

Both the calibre and length of the airways enlarge with increases in lung volume (Macklin, 1929; Di Rienzo, 1949). The net effect of these opposing actions on R_{aw}, in addition to other factors such as reflex changes in bronchomotor tone (Vincent *et al.*, 1970), is a curvilinear increase as the lung volume rises (Briscoe and DuBois, 1958; Blide, Kerr and Spicer, 1964; Bouhuys and Jonson, 1967). The R_r increases in a similar manner as R_{aw} constitutes its major component (Mead and Agostoni, 1964).

Studies on humans and cats suggest that R_{rt} constitutes 22-28% of the R_r in these species (Otis, Fenn and Rahn, 1950; Brody and DuBois, 1956).

The contribution that R_{lt} makes to R_l in humans and experimental animals has been reported as negligible (Fry *et al.*, 1954; Macklem and Mead, 1967), 2% (during mouth breathing, and 1% of R_{rt}) (Ferris, Mead and Opie, 1964), 30-40% (McIlroy *et al.*, 1955), approximately 18% (Marshall and DuBois, 1956), and 15-57% (Bachofen, 1968). The contribution that R_w makes to R_r has been reported as equalling approximately 29% during tracheostomy breathing in paretic or paralysed patients (Opie, Spalding and Stott, 1959), a small fraction during mouth breathing (Petit, Milic-Emili and Delhez, 1960), 16-19% (39% during mouth breathing) (Ferris, Mead and Opie, 1964), and some 30% during mouth breathing (Mead and Agostoni, 1964). Interspecies variation and the ventilatory conditions at the time of measurement (e.g. the lung volume and airflow; nasal, mouth or tracheostomised breathing) affect these values (Ferris, Mead and Opie, 1964), and must therefore be taken into consideration when comparing these data.

The Respiratory Resistances During Exercise

Aerobic exercise is not associated with changes in the functional residual capacity (FRC), or the R_l at fixed airflows, but E_l increases significantly (Stubbing *et al.*, 1980). However, some increase might be expected in the dynamic resistances because of the increased airflows, and the E_r would be expected to rise if the tidal volume (V_T) becomes sufficiently large for the lung volume to reach the less compliant region of the static P-V curve. This effect is enhanced because the increase in the inspiratory direction of the tidal volume during exercise is accomplished by the chest wall being distorted from its relaxed configuration, so that E_w increases (Grimby, Bunn and Mead, 1968; Goldman, Grimby and Mead, 1976).

Interspecies Variation in the Respiratory Resistances

The literature contains numerous reports on the elastic and dynamic respiratory resistances of human subjects and experimental animals. These data are however, influenced by many factors and experimental conditions (e.g. anaesthesia; muscle relaxants; mouth, nasal or tracheotomised breathing; body position, lung volume and airflow at the time of study). A major compilation of respiratory mechanics data for the purpose of interspecies comparison would therefore be seriously limited by the wide variety of experimental conditions and methods employed. Such a compilation will therefore not be presented.

Interspecies comparisons of the respiratory resistances have been reported (Agostoni, Thimm and Fenn, 1959; Drorbaugh, 1960; Crosfill and Widdicombe, 1961; Bennett and Tenney, 1982). Table 1.1 contains results from these studies, in addition to relevant sheep, goat, and human data from other sources. Although the data presented can by no means be considered extensive, they are sufficient to appreciate the considerable interspecies variation which exists.

Inertial Resistances

Inertial forces must be overcome during both inhalation and exhalation. However, the results of studies on humans and experimental animals support the view that the inertance of the lungs (Mead, 1956; Jackson, Watson and Kotlikoff, 1984) and the total respiratory system (Brody *et al.*, 1956; Du Bois *et al.*, 1956; Jackson, Watson and Kotlikoff, 1984) make a negligible contribution to the total resistance to breathing, particularly at resting ventilations.

STATIC AND DYNAMIC LUNG VOLUMES

Static Lung Volumes

Both the lungs and thoracic structures exert strong retractive elastic recoils at the total lung capacity (TLC). The TLC is therefore determined by the balance between the elastic recoil of the inflated respiratory system and the inspiratory muscle strength, but factors such as glottic closure and antagonistic (abdominal) muscle activity also play a role (Mills, 1950; Campbell and Green, 1953; Mead, Milic-Emili and Turner, 1963).

The thoracic structures exert a strong expansive elastic recoil at the residual volume (RV), which is opposed by a weak retractive lung recoil. The RV is therefore determined by the balance between the elastic recoil of the deflated respiratory system and the expiratory muscle strength. Airway closure from dynamic airway compression also plays a role in older subjects (Leith and Mead, 1967). Diaphragmatic activity occurs at the end of maximal expirations (Agostoni and Rahn, 1960; Agostoni and Torri, 1962), and therefore also limits the RV.

Table 1.1 Respiratory resistances of some mammalian species

	C_l	C_w	C_r	R_l	R_r	Source
rat			0.4		-	Agostoni, Thimm and Fenn, 1959
guinea-pig			1.3		60.0	
rabbit			4.2		29.6	
cat			10.1		14.3	
dog			26.6		3.9	
mouse			0.029			Drorbaugh, 1960
rat			0.148			
rabbit			2.4			
dog			30			
mouse	0.049	0.33	0.043*	480		Crosfilland Widdicombe, 1961
rat	0.39	1.47	0.31*	90		
guinea-pig	1.26	3.66	0.94*	59		
rabbit	6.0	9.4	3.66*	25		
monkey†	12.3	7.3	4.59*	8.6		
cat	13.4	13.4	7.00*	11.5		
dog	40	32	17.78*	1.3		
mouse	0.03	0.07	0.032		1751	Bennett and Tenney, 1982
rat	1.1	1.2	0.57		161.7	
rabbit	4.3	13.1	2.8		38.5	
cat	16.7	34.5	10.5		20.3	
dog	24.3-71.4	91.4-182	18.5-51.3		8.0	
goat	105-107	78-107	50.0			Avery and Cook, 1961
sheep	98-115			1.5-1.8		Colebatch and Halmagyi, 1961
sheep	120			1.4		+Reinhart *et al.*, 1979
sheep	73			1.15		+Hutchison *et al.*, 1983
human	100-150	200	60-85	0.5-6.0		Nunn, 1977

Compliances are in ml.cm H_2O^{-1}; dynamic resistances are in cm H_2O.sec.L^{-1}

† Species not stated

* Calculated from C_l and C_w data where $\frac{1}{C_r} = \frac{1}{C_l} + \frac{1}{C_w}$

\+ Data from conscious subjects; all other data from anaesthetized or euthanised subjects

Values in R_r column for Agostoni's data refer to viscous component only.

Dynamic resistances do not include upper airways resistance.

The relaxation volume or functional residual capacity represents the lung volume where the retractive recoil of the lungs is exactly counterbalanced by the expansive recoil of the thoracic structures. The lungs will therefore attain this volume if the airways are open to the atmosphere and the respiratory muscles are relaxed. The FRC is generally accepted as equalling the end-expiratory lung volume (EELV) during quiet breathing, so that these terms are frequently used synonymously. However, muscular paralysis is frequently associated with reductions in the EELV (Froese and Bryan, 1974; De Troyer and Bastenier-Geens, 1979), an effect which may be the result of tonic inspiratory muscle activity (Muller *et al.*, 1979).

Dynamic Lung Volumes

Timed lung volumes from a single forced expiration consist of the timed volumes or airflows exhaled during maximum dynamic expiratory manoeuvres commencing at the TLC. More specifically, they are measured as the volume exhaled after a given time (e.g. the forced expiratory volume after one second - FEV_1), the airflow when a set percentage of the vital capacity (VC) has been exhaled (e.g. the maximal expiratory flow at 50% of the exhaled VC - $MEF_{50\%}$), and the mean airflow over a set range of lung volumes (e.g. the mean maximal expiratory flow at 50 to 75% of the exhaled VC - $MMEF_{50-75\%}$). The maximum expiratory flow-volume (MEFV) curve represents the relationship between airflow and lung volume during such expirations.

A theoretical analysis of the dynamic lung volumes obtained from a forced expiration is best appreciated from the isovolume transpulmonary pressure-airflow relationship during expirations of varying effort, as described by Fry *et al.* (1954). The expiratory airflows at the lower lung volumes peak during submaximal efforts, and greater efforts (i.e. higher transpulmonary pressures result in decreases, rather than increases in $\dot{V}$ (Hyatt, Schilder and Fry, 1958; Fry and Hyatt, 1960). A detailed discussion of the mechanisms which produce such airflow maxima is beyond the scope of this review but is provided by Fry and Hyatt (1960). Briefly, they are the result of dynamic compression of the intrathoracic airways which occurs during forced expirations. The intrapleural pressure exerts two opposing actions on $\dot{V}$ under these conditions: (1) by acting as the driving pressure, so that increases in pressure elevate $\dot{V}$, and (2) by exerting a compressional

force on the outer surface of the intrathoracic airways, so that increases in pressure increase the flow resistance and thereby decrease $\dot{V}$. The expiratory airflow maxima at any given lung volume therefore represents the point where these two effects exactly counterbalance. At lower transpulmonary pressures the initial effect dominates, whilst the latter prevails at higher pressures and leads to some decrease in $\dot{V}$. Such airflow maxima are not observed during inspirations because the intrapleural pressure then exerts an airway dilating effect.

Expiratory airflow maxima are not observed over the upper half or third of the VC (Hyatt, Schilder and Fry, 1958; Hyatt, 1965). Increases in the expiratory driving pressure (as a result of increased expiratory muscle strength for example) will therefore increase those indices measured over this lung volume range (e.g. peak expiratory flow - PEF), whereas those measured over lower lung volumes will be little affected. Increases in the TLC (as a result of increases in the inspiratory muscle strength for example) will elevate the effort-dependent timed volumes, and to a lesser extent, the effort-independent timed volumes such as the $MEF_{75\%}$.

The MBC and MVV_s

The maximum breathing capacity (MBC) is the theoretical maximum minute volume of ventilation which can be maintained for short periods of time, whereas the maximum voluntary ventilation (MVV) may be defined as the level of ventilation which is measured during voluntary maximum hyperventilation. The MBC is best estimated by MVV manoeuvres which are maintained for 10 to 30 seconds (Hyatt, 1965; Freedman, 1970), as the maximum achievable ventilation decreases markedly over longer periods (Tenney and Reese, 1968; Freedman, 1970; Leith and Bradley, 1976). The MVV plateaus after some 10 minutes of sustained effort, to a level which equals approximately 50-86% of the MBC (Zocche *et al.*, 1960; Tenney and Reese, 1968; Leith and Bradley, 1976; Keens *et al.*, 1977). This sustainable level of the MVV can be maintained for long periods and will be referred to as the MVV_s, whereas the short-term measurements of the MVV (e.g. MVV_{15sec}) will be referred to as the MBC.

The pressure-airflow relationship during the expiratory phases of the MBC manoeuvre is essentially identical to that of a maximum effort VC

manoeuvre performed over the same lung volume range with airflow maxima occurring as a result of dynamic airway compression (Mead and Agostoni, 1964; Hyatt, 1965). Near-maximum airflows also occur during most of the inspiratory portions of the MBC (Hyatt, 1965). The MBC is therefore dependent on the patency and flow resistance of the airways, especially the compressible intrathoracic airways. It is however, also limited by the speed of shortening of the respiratory musculature and the rate at which these muscles are "able to mobilize chemical potential energy for the performance of work" (Agostoni and Fenn, 1960; Mognoni *et al.*, 1968). Other factors which influence the MBC include the respiratory muscle strength and the elastic respiratory resistances, so that a precise interpretation of this respiratory mechanics index is not possible (Hyatt, 1965).

The MVV_s is considerably lower than the MBC, and is therefore less dependent on the maximum speed of respiratory muscle contraction and the flow resistance of the intrathoracic airways. However, the prolonged nature of the MVV_s test makes it highly dependent on the endurance of the respiratory musculature.

THE WORK OF BREATHING

The respiratory system acts as a pump, driving air from the atmosphere to the alveoli, and back to the atmosphere. All pumps operate on less than a 100% efficiency. That is to say, the total energy expended by the pump always exceeds the useful mechanical work performed. Consequently, the methods for measuring respiratory work can be classified into two groups. The first measures the mechanical work performed on the respiratory system and the ventilated gases, while the second measures the total energy cost of breathing by determining the oxygen consumption ($\dot{V}_{O_2}$) of the respiratory muscles ($\dot{V}_{O_2r}$).

Mechanical Work of Breathing

The total mechanical work performed on the respiratory system per breath ($W_{m(r)}$) is the sum of that performed on the lungs and ventilated gases (W_l) and the thoracic structures (W_w), each of which have elastic and dynamic components. A useful feature of measuring respiratory mechanics in terms of mechanical work is that the elastic and dynamic resistive components are expressed in the same units.

Total mechanical work of breathing

The total dynamic, total elastic, and total mechanical work of breathing cannot be measured during spontaneous ventilation (Otis, Fenn and Rahn, 1950; Mead and Whittenberger, 1953; Otis, 1954). Such measurements can however, be made when the subject's respiratory system is artificially ventilated (Otis, Fenn and Rahn, 1950; Otis, 1954). A prerequisite condition for such measurements is complete relaxation of the respiratory muscles so that the respirator pump performs all the work of breathing (Otis, Fenn and Rahn, 1950; Otis, 1954; Sharp *et al.*, 1964a). Muscular relaxants have been recommended for this purpose (Sharp *et al.*, 1964a), although deep anaesthesia has also been used (Comroe, Nisell and Nims, 1954).

Otis, Fenn and Rahn (1950) developed formulae from which $W_{m(r)}$ and its elastic and dynamic components could be calculated given that the respiratory resistances, V_T, and respiratory frequency (f_r) are known. Equations 2 and 3 represent the rate at which $W_{m(r)}$ ($\dot{W}_{m(r)}$) is performed under conditions of passive and active expiration respectively,

$$\dot{W}_{m(r)} = \tfrac{1}{2}E_r f_r V_T^2 + \tfrac{1}{4}K' \Pi^2 f_r^2 V_T^2 + \tfrac{2}{3}K'' \Pi^2 f_r^3 V_T^3 \quad (2)$$

$$\dot{W}_{m(r)} = \tfrac{1}{2}K' \Pi^2 f_r^2 V_T^2 + \tfrac{4}{3}K'' \Pi^2 f_r^3 V_T^3 \quad (3)$$

The three components of equation 2 respectively represent the elastic, dynamic viscous, and dynamic nonviscous components of $\dot{W}_{m(r)}$. Both equations 2 and 3 assume that the airflow-time relationship of respiration is sinusoidal, and in the case of 2 that E_r is constant over the range of lung volumes encountered. In the case of equation 3, it is further assumed that the viscous and dynamic nonviscous resistances during expiration equal that during inspiration, and that the elastic energy stored during inspiration assists the expiratory muscles in overcoming the dynamic resistances opposing expiration. These equations are therefore limited in their ability to precisely calculate mechanical respiratory work, and their real value are as an aid for understanding the interrelations between some of the factors determining mechanical respiratory work (Otis, Fenn and Rahn, 1950).

Equation 3 may be rewritten as

$$\dot{W}_{m(r)} = \dot{W}_{dyn(i)} + \dot{W}_{dyn(e)} \quad (4)$$

where $\dot{W}_{dyn(i)}$ and $\dot{W}_{dyn(e)}$ respectively denote the rates of total dynamic work expended during inspiration and expiration. Margaria *et al.* (1960) used this relationship to determine $\dot{W}_{m(r)}$ during the raised minute ventilations associated with exercise. These workers measured the dynamic work performed on the lungs and ventilated gases, and under the conditions of active expiration assumed it to equal $W_{m(r)}$. Similar measurements have been made by Milic-Emili and Petit (1960) and Milic-Emili, Petit and Deroanne (1962). Such measurements do not include the dynamic work performed on the thoracic structures. As previously discussed, R_w makes a significant contribution to R_r although the R_w to R_r ratio decreases as the ventilation increases (Mead and Agostoni, 1964).

Inspection of equations 2 and 3 reveals that increasing f_r without changing the minute ventilation will produce decreases in $W_{m(r)}$, decreases in $\dot{W}_{m(r)}$ when expiration is passive, and not affect $\dot{W}_{m(r)}$ when expiration is active. It is also apparent that the $W_{m(r)}$ expended per litre of ventilation rises as the minute ventilation increases, and that the ratio of elastic to dynamic work performed is dependent on the minute ventilation, f_r, and V_T. Calculations based on the data from Milic-Emili and Petit (1960) indicate that the $W_{m(r)}$ equals some 55 x 10^3gcm.L^{-1} at minute ventilations of 100 L.min^{-1}. However, as previously discussed, their measurements did not include the dynamic work performed on the thoracic structures. The $W_{m(r)}$ has been estimated as equalling some 125 x 10^3gcm.L^{-1} during the 15 second MBC (average ventilation of 187 L.min^{-1}) (Milic-Emili *et al.* 1964), but these measurements did not include the dynamic work performed on thoracic structures other than the abdomen.

As previously discussed, aerobic exercise increases the elastic resistance to breathing. However, this will not materially alter $W_{m(r)}$ if the minute ventilation is sufficiently high for expiration to be active, because $W_{m(r)}$ equals the sum of the inspiratory and expiratory dynamic work components under these conditions. Calculations based on the data from Margaria *et al.* (1960) and Milic-Emili, Petit and Deroanne (1962) suggest that $W_{m(r)}$ equals some 21-25 x 10^3gcm.L^{-1} at exercise workloads which are associated with minute ventilations of 100 L.min^{-1}, whereas workloads which exhausted the subjects within 3-6 minutes (ventilation equalled

120 $L.min^{-1}$) were associated with $W_{m(r)}$ values of 25-32 x 10^3 g cm.L^{-1}. Such measurements have also been made on dogs during exercise, and the mechanical respiratory work expended per litre of ventilation was found to decrease during hyperthermia (Saibene *et al.*, 1981).

Table 1.2 presents a summary of published mechanical respiratory work data from humans and experimental animals during resting and moderately elevated levels of ventilation. Measurements of $W_{m(r)}$ from dynamic P-V plots suggest that some 4200-7300 g·cm of mechanical work are performed per litre of ventilation. However, the indirect method of estimating $W_{m(r)}$ developed by Campbell, Westlake and Cherniack (1957), and also used by Cherniack (1959) have yielded values of 8000-23000 g cm.L^{-1}. Interspecies differences are also apparent, a factor which is consistent with the interspecies variation in the respiratory resistances (refer to Table 1.1). Elastic work appears to be the major component of $W_{m(r)}$ at these levels of ventilation.

Total Energy Cost of Breathing

The total energy cost of breathing is determined by measuring the change in $\dot{V}_{O_2}$ per unit change in the minute ventilation (Cherniack, 1959; Fritts *et al.*, 1959). The respiratory oxygen cost ($\dot{V}_{O_2r}$) may then be converted to equivalent energy units (Fritts *et al.*, 1959). The results of a number of $\dot{V}_{O_2r}$ studies on humans and experimental animals are presented in Table 1.3. As can be seen, the reported values vary considerably for human subjects, and at resting levels of ventilation equal some 0.2 to 0.7 ml of O_2 per litre of ventilation (52 to 144 g cm x $10^3.L^{-1}$). Values for these parameters appear to differ in other species.

As the respiratory muscles must perform more work to provide a raised ventilation, an increased minute ventilation will require a higher total respiratory energy cost (W_r) per unit time ($\dot{W}_r$). Furthermore, the relationship between $\dot{W}_r$ and minute ventilation is curvilinear, with increases in ventilation requiring progressively greater increases in $\dot{W}_r$ (Campbell, Westlake and Cherniack, 1957; Milic-Emili and Petit, 1960). The total energy cost of breathing per litre of ventilation must therefore also increase as the minute ventilation rises. Bartlett, Brubach and Specht (1958) have estimated that the $\dot{V}_{O_2r}$ equals some 10 ml of O_2 per litre of ventilation (W_r = 2060 x 10^3 g cm.L^{-1}) at ventilations of 200 $L.min^{-1}$. A stage will therefore be reached where a further increase in the minute volume

Table 1.2 Mechanical work of breathing data from the literature

Minute ventilation ($L.min^{-1}$)	W_l Elastic	W_l Dynamic	W_l Total	W_w Elastic	W_w Dynamic	W_w Total	$W_{m(r)}$ Elastic	$W_{m(r)}$ Dynamic	$W_{m(r)}$ Total	Reference
-(V_T=0.269L)	5335	1216	6551				7955	1550	9505	Dean and Visscher, 1941+ϕ
7.5							2660	1522	4182	Otis, Fenn and Rahn, 1950
8.7	2346	1054	3400							McIlroy, Marshall and Christie, 1954
resting level (assume 5)									8000	Campbell, Westlake and Cherniack,1957
2.12							2196	407	2603	Agostoni, Thimm and Fenn, 1959†§ϕ
0.914							1682	694	2376	
0.74							2612	1224	3836	
0.26							1372	853	2225	
8.9									22700	Cherniack, 1959
7.57									5544	Eldridge and Davis, 1959
≃ 10			4300							Fritts *et al.*, 1959
6.1-6.8	1313-1478									Colebatch and Halmagyi, 1961*
0.026			2540							Crosfill and Widdicombe, 1961‡ϕ
0.164			2940							
0.130			2090							
0.634			2370							
0.706			1157							
0.977			1900							
2.860			2350							
20			3500			3800			7300	Sharp *et al.*, 1964a

Mechanical respiratory work data expressed in g cm.L^{-1} of ventilation. Dynamic work does not include that performed during expiration.

† Data from dogs, cats, rabbits and guinea-pigs, respectively

‡ Data from mice, rats, guinea-pigs, rabbits, monkeys (species not stated), cats and dogs, respectively

* Data from sheep

\+ Data from dogs

§ Tabulated values calculated from published data

ϕ Work data do not include the dynamic component required for upper R_{aw}

Table 1.3 Total energy cost of breathing

	Minute ventilation ($L.min^{-1}$)	$\dot{V}_{O_2r}$ ($ml\,O_2.L^{-1}$)	W_r† ($g\,cm \times 10^3.L^{-1}$)	Reference
horse		2.2	453	Zuntz and Hagemann 1898
human	resting ventilation+25	1	206	Courmand *et al.* 1954
	resting ventilation+50	2	412	
	resting ventilation+80	3.2	659	
human	≃ 160	≃ 3.5	≃ 721	McKerrow and Otis 1956
human	up to 40	0.25	52	Campbell, Westlake and
	up to 80	0.6	124	Cherniack 1957
human	≃ 200	≃ 10	≃2060	Bartlett, Brubach and Specht 1958
human	resting ventilation+6 to 10	1.16	239	Cherniack 1959
	resting ventilation+30	< 2	< 412	
human	≃ 10	≃ 0.7	≃ 144	Fritts *et al.* 1959
	≃ 20	≃ 0.9	≃ 185	
	≃ 30	≃ 1.2	≃ 247	
	≃ 40	≃ 1.4	≃ 288	
	≃ 50	≃ 1.6	≃ 330	
	≃ 60	≃ 2.2	≃ 453	
	≃ 70	≃ 3.1	≃ 639	
human	38	≃ 0.18	≃ 37	Milic-Emili and Petit
	65	≃ 0.31	≃ 64	1960
	84	≃ 0.50	≃ 103	
	89	≃ 0.56	≃ 115	
human	90-130	4.3-4.4	886-906	Shephard 1966*
ox (calves)	10-90	4	824	Hales and Findlay 1968
human	70	4.2	865	Levison and Cherniack 1968+
dog	5.58	0.269	55	Robertson, Pagel and
	14.36	0.311	64	Johnson 1977
	23.06	0.327	67	

† W_r ($g\,cm \times 10^3.L^{-1}$) values calculated from corresponding $\dot{V}_{O_2r}$ data ($ml\,O_2.L^{-1}$) by multiplying the latter by 206 (Fritts *et al.*, 1959)

* Subjects exercising at 80% of the maximum aerobic work capacity

\+ Subjects exercising at submaximal workloads

of ventilation requires a greater increase in $\dot{V}_{O_2r}$ than the additional oxygen absorbed, so that the arterial oxygen tension falls. The level of ventilation at which this occurs has been estimated to equal 140 (Otis, 1954), 130-170 (Margaria *et al.*, 1960), 150 (Otis, 1964) and 120 $L.min^{-1}$ (Shephard, 1966).

The $\dot{W}_{m(r)}$-minute ventilation relationship at least partially accounts for the similar relationship between $\dot{W}_r$ and minute ventilation (Otis, Fenn and Rahn, 1950). This requires that the mechanical efficiency of the respiratory system (RE) is constant over a wide range of ventilations, as the RE is defined as the ratio of $W_{m(r)}$ to W_r. Milic-Emili and Petit (1960) observed that RE was relatively constant over a wide range of minute ventilations, although decreases have been reported (McKerrow and Otis, 1956; Fritts *et al.*, 1959).

The W_r during heavy exercise is high. Shephard (1966) estimated that the $\dot{V}_{O_2r}$ equalled some 4.3 ml $O_2.L^{-1}$ (W_r = 886 g $cm.L^{-1}$) over the ventilatory range (90-130 $L.min^{-1}$) elicited by exercise at 80% of the maximum aerobic work capacity. Levison and Cherniack (1968) reported that $\dot{V}_{O_2r}$ equalled 4.2 ml $O_2.L^{-1}$ during submaximal exercise (ventilation equalled 70 $L.min^{-1}$).

CHAPTER 2

EFFECTS OF ENDURANCE TRAINING ON RESPIRATORY MECHANICS AND ENDURANCE

INTRODUCTION

Little is known regarding the effects of endurance training on the respiratory resistances and work of breathing, or whether such effects make a significant contribution to improvement in the performance of endurance activities. This review examines the relevant literature and covers a range of exercise types and training regimes, as well as a variety of respiratory mechanics parameters which include the static and dynamic lung volumes. The findings to be discussed were obtained from healthy adult human subjects unless specified otherwise.

PRINCIPLES OF EXERCISE TRAINING

Training-related adaptations are dependent on both the type of training exercise and the training regime. Exercise training may be defined as the regular engagement in physical activity which is aimed at improving the performance of such exertions. It may be divided into two main types - strength training and endurance training. The former results in increases in the maximum tension that skeletal muscles can generate, while the latter enhances the subject's ability to perform sustained physical exertion.

Exercise places an increased demand on various physiological functions. Repeated exposure to such stress can modify these functions in a manner which allows improvements in exercise performance. The nature of such adaptations is therefore dependent on the types of exercise and training regime employed, as these determine which organ systems are stressed.

Astrand and Rodahl (1977) summarized the types of training as those which "the main demand is centered on (1) muscle strength without a major increase in the total oxygen uptake; (2) aerobic processes without significantly mobilizing anaerobic processes; (3) anaerobic processes without maximal taxation of the oxygen-transporting organs; and (4) both aerobic and anaerobic processes simultaneously. The alternatives 2 and 4 do not entail maximal taxation of muscle strength; alternative 3 does not

necessarily require maximal strength". Exercise may therefore improve performance in the type of physical activity for which one is training, but often has little effect on other forms of activity. Thus the diversity of exercise types and training regimes employed in the studies discussed in this review will lead to a variety of different physiological adaptations. This factor must be considered when interpreting the results of these studies.

Training sessions must be of sufficient intensity, duration, and frequency to elicit an observable adaptive response (Müller, 1970; Astrand and Rodahl, 1977; American College of Sports Medicine, 1978). The extent of this response is also dependent on the total duration of the training regime. Programmes which elicit optimal training responses cannot be stated in general terms because of variables which include the nature of the training effect sought, and individual differences such as subject age and level of fitness. The intensity, duration, and frequency of the training stimulus must however be above certain minimum levels to produce training-related adaptations.

Strength Training

Increases are observed in the maximum tension of skeletal muscles which are subjected to contractions exceeding 50% of the maximum voluntary contraction strength (Josenhans, 1967). Stronger training contractions lead to a more rapid increase in strength (Müller, 1970). In many subjects, optimal strength training results from a single maximal contraction lasting one second, and performed daily, although some subjects require some three to six daily repetitions to achieve this response (Müller, 1970).

Endurance Training

The performance of sustained exertions can be improved by increasing the maximal anaerobic and aerobic powers (the maximum rates of energy outputs from anaerobic and aerobic processes).

Anaerobic power: The energy required for brief periods (10-15 seconds) of maximal work separated by rest periods of at least several minutes is primarily derived from anaerobic processes, so that this type of activity theoretically constitutes an anaerobic training stimulus. Repeated maximal exertions lasting 1 minute and separated by rest period of 4-5 minutes

duration probably serve as an effective regime for developing the anaerobic power (Astrand and Rodahl, 1977).

Aerobic power: Improvements in the aerobic power are achieved by physical activities which exert a major load on the oxygen transporting organs. Repeated bouts of exercise which utilize large muscle groups for 3-5 minutes followed by periods of rest or light activity of an equal duration, are a suitable means for this purpose (Astrand and Rodahl, 1977). The American College of Sports Medicine (1978) has made the following recommendations for endurance training regimes aimed at developing and maintaining aerobic fitness in the healthy adult: 1. Frequency of training 3 to 5 days per week; 2. Intensity of training - sufficient to elicit 60 to 90% of the maximum heart rate, or 50 to 85% of the maximum $\dot{V}_{O_2}$; 3. Duration of training - 15 to 60 minutes of continuous aerobic activity, with exercise of low workloads requiring longer durations to achieve the same effect; 4. Mode of activity - exercise which utilizes large muscle groups, can be continuously maintained, and is rhythmical and aerobic in nature.

EXPERIMENTAL DESIGN

Scientific investigations which examine the physiological adaptations resulting from physical training follow one of two experimental designs (or both) - 1. the cross-sectional approach which compares data from well trained subjects with that from sedentary control subjects; and 2. the longitudinal approach in which the subjects act as their own controls with comparisons made between pre- and post-training data. Cross-sectional studies have been more commonly conducted because of the greater difficulties imposed by the longitudinal approach. However, it can be argued that regular participation in physical activities favours subjects with a superior natural endowment, and that the trained subjects in cross-sectional studies are therefore physically superior to the controls because of this bias rather than any training-related adaptations. This argument is especially relevant if the trained group includes or consists of high class sports competitors. The potential importance of this bias can be appreciated when one realizes that many of the studies dealing with endurance training and respiratory mechanics in this review were cross-sectional in design.

ENDURANCE TRAINING AND THE STATIC AND DYNAMIC LUNG VOLUMES

Table 2.1 summarizes data from a selection of studies which examined the relationship between endurance training and the static and dynamic lung volumes.

Static Lung Volumes

Encurance training is rarely associated with changes in the TLC, RV, VC, and FRC (refer to Table 2.1). However, endurance athletes frequently posess higher vital capacities than sedentary subjects, which appears to result from an increase in TLC. The higher VC and TLC of athletes may however, be due to a selective bias which favours subjects with a superior endowment. Breath-hold diving is associated with increases in the TLC which are believed to result from training-related increases in the inspiratory muscle strength (Carey, Schaefer and Alvis, 1956; Song *et al.*, 1963). A similar effect may occur with some forms of endurance training such as oarsmanship (Cotes, 1979).

Underwater diving exerts a raised workoad on the respiratory system because of the increased air density. Chronic exposure to this form of activity is associated with increases in the VC and possibly other static lung volumes, but the C_1 is not altered (Fisher *et al.*, 1970; Crosbie, Reed and Clarke, 1979). These workers considered their findings suggestive of increases in respiratory muscle strength.

The results of the above-mentioned studies suggest that endurance training does not alter the elastic respiratory resistances.

Dynamic Lung Volumes

The MBC and MVV_s

Endurance training is frequently associated with increases in the MBC and MVV_s (refer to Table 2.1). The increase in MBC may theoretically result from training-related increases in the maximum anaerobic capacity, strength, and maximum contraction velocity, of the respiratory musculature. Swim training is associated with increases in the MEP of adolescents (Newman, Smalley and Thomson, 1961) and ventilatory muscle endurance

Table 2.1 Endurance training-related adaptations in static and dynamic lung volumes

Study design	Type of exercise	Training regime	Training-related adaptations: Static and dynamic lung volumes	Other	Reference
X.S	not specified	trained group consisted of athletes from various varsity teams	VC I^{+};MBC_{12sec} NE^{*}	-	Stuart and Collings 1959
X.S	not specified	trained group consisted of subjects who had trained systematically and strenuously for several years	TLC I;RV I;VC I; MBC I	$\dot{V}_{O_2max}$ (per kg body-weight) I	Milic-Emili, Petit and Deroanne, 1962
X.S	running	trained group consisted of international class runners with best performance in 440 yards-6 mile distances	TLC NE; RV I?;VC I?;FEV_1 I?	$\dot{V}_{O_2max}$ I	Newman, Smalley and Thomson 1962
X.S	rigorous endurance training	trained group consisted of superbly trained athletes	VC I;MBC I;$MEF_{75\%}$ NE; $MEF_{50\%}$ NE; $MEF_{25\%}$ NE	-	Shapiro *et al.* 1964
X.S	long distance running and interval training	trained group participated in many years of 1-1.5 hrs.day^{-1}, 2-6 days.$week^{-1}$, for at least 8 months.$year^{-1}$	VC NE;MBC I;FEV_1 I	$\dot{V}_{O_2max}$ I	Grimby and Saltin 1966
Long.	aerobic treadmill training	3-6 weeks of treadmill exercise at 3-5 mph and 0-6% slope for 5-20 min.day^{-1}, 1-5 days.$week^{-1}$	MBC_{15sec} I?	aerobic work capacity I	Shephard 1967
Long.	swim training	4 months of swim training	TLC NE;RV D^{ϕ}; VC I; FRC D	-	Bachman and Horvath 1968
Long. & X.S.	distance running, weight training, general calisthenics, and specific oarsmanship training	5 months of rigorous training	TLC NE;RV NE;VC NE;MBC I;FEV_1 NE	heart rate at rest and at set workloads D	Reuschlein *et al.* 1968
Long.	running and bicycle pedalling	subjects participated in a period of intermittent training and a period of continuous training, 5-6 days.$week^{-1}$for 53-55 days	TLC NE;RV NE;VC NE;FEV_1 NE	$\dot{V}_{O_2max}$ I; heart rate at set submaximal workloads D	Saltin *et al.* 1968
Long.	ventilatory muscle endurance training	subjects participated in programme of 30 min.day^{-1}, 5 days.$week^{-1}$, training for 5 weeks	TLC NE;RV NE;VC NE;FRC NE;MBC_{15sec} I;MVV_s I;$MEFV_{curve}$ NE	-	Leith and Bradley 1976
X.S.	middle and long distance running	trained group consisted of elite class, middle and long distance runners	TLC I;VC I;RV NE; FEV_1 NE	-	Raven 1977
Long.	ventilatory muscle endurance training	subjects participated in programme of 25 min.day^{-1}, 5 days.$week^{-1}$ training for 4 weeks	MEC_{12sec} NE;MVV_s I; FEV_1 NE;$MMEF_{25-75\%}$ D^{ϕ}	-	Keens *et al.* 1977
X.S.	marathon running	trained group consisted of athletes who had each run a marathon in less than 2 hr 55 min recently; run 109 kilometers.$week^{-1}$	TLC NE;RV NE;VC NE; MBC NE;FEV_1 NE; $MEF_{50\%}$ NE	V_{O_2max} I	Mahler, Moritz and Loke 1982
Long. & X.S.	running intersperced with walking so that heart rate was at 80% of maximum	at least 40 min.day^{-1}, 3 times.$week^{-1}$ for 20 weeks	TLC NE;RV NE;VC NE; FRC NE;MBC_{12sec} I; MVV_{15min} I; FEV_1 NE	-	Robinson and Kjeldgaard 1982

Note: X.S. cross-sectional; Long. longitudinal

$^{+}$ I denotes increase; * NE denotes no effect; $^{\phi}$ D denotes decrease.

training is accompanied with increases in the MBC_{15sec}, MEP and MIP (Leith and Bradley, 1976). Robinson and Kjeldgaard (1982) observed increases in the MEP, MBC_{12sec}, and MVV_{15min} following a 20 week training period of endurance running. However, increases in the MEP and MIP from ventilatory muscle strength training are not associated with changes in the MBC (Leith and Bradley, 1976). Furthermore, training-related increases in the MBC are difficult to interpret solely in terms of a superior respiratory musculature because effort-independent airflow maxima are observed during the expiratory phase of the MBC manoeuvre (Hyatt, 1965). Shapiro *et al.* (1964) suggested that trained individuals may be able to breath at higher lung volumes during these manoeuvres and thereby encounter lower flow resistances. Alternatively, the raised MBC may be indicative of an endurance training-related decrease in R_{aw}.

As with other skeletal muscles, the endurance of the respiratory musculature can be raised by endurance training, as evidenced by increases in the MVV_s (Leith and Bradley, 1976; Keens *et al.*, 1977; Bradley and Leith, 1978). The maximum sustainable level of $\dot{V}_{O_2r}$ is raised by ventilatory muscle endurance training (Bradley and Leith, 1978), so that the aerobic capacity of these muscles is increased. Endurance training is associated with increases in the proportion of slow-to fast-twitch muscle fibres in the diaphragms of guinea-pigs (Leiberman, Maxwell and Faulkner, 1972). Biochemical changes suggestive of increased glycolytic and aerobic capacities of the rat diaphragm have also been reported following such training (Ianuzzo *et al.*, 1982). Chronic elevation of the respiratory load by tracheal banding is associated with similar changes in the aerobic capacity of the rat respiratory musculature, and increases in the proportion of slow-to fast-twitch diaphragmatic fibres (Keens *et al.*, 1978). Such changes are similar to those observed in other skeletal muscles, and are consistent with improvements in the endurance of these muscles (Keens *et al.*, 1978; Keens, 1979).

The MBC and MVV_s represent the maximum short term and long term performances of the respiratory system as a pump, and are therefore dependent on many factors which include the respiratory resistances and the RE. Training-related increases in the MBC and MVV_s may therefore be indicative of decreases in the respiratory resistances or increases in the RE.

Timed lung volumes from a single forced expiration

The infrequent reports of endurance training-related increases in the FEV_1 come from cross-sectional studies, whereas longitudinal studies reveal no change (refer to Table 2.1). This discrepancy may be the result of athletes from cross-sectional studies having a superior natural endowment than the sedentary control subjects.

Endurance training by swimming may be associated with increases in the FEV_1 which result from increases in the expiratory muscle strength. The findings by Newman, Smalley and Thomson (1961) are consistent with this argument, but the longitudinal study by Robinson and Kjeldgaard (1982) revealed that distance running training was associated with increases in the MEP while FEV_1 was not affected. Leith and Bradley (1976) observed increases in the MEP of subjects exposed to a five week programme of ventilatory muscle strength training, but failed to detect any significant change in the MEFV curve. Shapiro and co-workers (1964) found no difference between the $MEF_{25\%}$, $MEF_{50\%}$, and $MEF_{75\%}$ of superbly trained endurance athletes and sedentary subjects. Keens *et al.* (1977) observed no significant change in the $MMEF_{25-75\%}$ after a four week programme of ventilatory muscle endurance training. These findings suggest that, during high airflows, R_{aw} is not altered by endurance training. However, this cannot be considered as conclusively proven because it does not agree with the observed effects on the MBC, and because of the limited value of these parameters as indices of R_{aw}.

ENDURANCE TRAINING AND THE RESPIRATORY RESISTANCES

Dynamic Respiratory Resistances

The respiratory flow resistances of endurance-trained subjects has been compared with that of untrained controls (Newman, Smalley and Thomson, 1961; Shapiro *et al.*, 1964). Measurements were made during maximum dynamic respiratory manoeuvres in both studies. In the former study, elite adolescent swimmers were found to possess a higher MEP/FEV_1 ratio (taken as an index of R_r) than control subjects. However, this index may not have given a reliable estimate of R_r. The MEP of the trained subjects were significantly higher than that of the controls. The FEV_1 is a partially effort-independent

timed lung volume, so that a given increase in the MEP would be accompanied with the smaller reported rise in the FEV_1. This would therefore result in an increase in R_r as measured in this study. Shapiro and co-workers reported that the R_1 during maximum inspiratory and expiratory manoeuvres was somewhat elevated in athletes, although not significantly. Increased transpulmonary pressure gradients would raise R_1 during these manoeuvres (Mead and Whittenberger, 1953), and could have been generated by a superior respiratory musculature in the athletic group.

Milic-Emili, Petit and Deroanne (1962) did not observe any significant differences between the dynamic W_1 (per litre of ventilated gas) of trained and untrained subjects at raised minute ventilations during exercise.

Chronic exposure to underwater diving is associated with increases in the MBC but does not appear to alter the R_1 at resting levels of ventilation or forced expiratory dynamic lung volumes (Fischer *et al.*, 1970). However, a more recent study suggests that airway obstruction may occur (Crosbie, Reed and Clarke, 1979), so that the results of these studies are inconclusive.

A review of the literature failed to locate any studies which examined the relationship between endurance training and R_w.

There is a paucity of data available in the literature on the effect of endurance training on the dynamic respiratory resistances. The few available studies indicate that little, if any, endurance training-related changes occur in R_1 during conditions of high airflow.

Elastic Respiratory Resistances

Very little work appears to have been published in this field. Leith and Bradley (1976) observed no change in the elastic properties of the respiratory systems of a group of human subjects who participated in a 5 week programme of either strength or endurance training which was restricted to the respiratory musculature. Chronic exposure to underwater diving does not appear to alter the C_1 (Fisher *et al.*, 1970).

Girth increases suggestive of hypertrophy of the thoracic musculature are observed when these muscles are engaged in strength training regimes (Wilmore, 1974). Regular exercise also appears to increase the rate of

bone deposition (Eisenberg and Gordan, 1961) so that gains in the thoracic bone mass may occur. Such training-related adaptations would mass load the thorax and consequently increase the E_w and E_r (Sharp *et al.*, 1964b; Peters, 1969). The latter author has commented on the reduced C_r in subjects with large, heavily boned and muscled chests.

The degree of muscular hypertrophy elicited by endurance training is less than that resulting from strength training (Saltin and Gollnick, 1983). This argues against a significant mass loading-related increase in E_w occurring as a result of endurance training of the thoracic musculature.

Increasing the lung volume stretches the expiratory musculature (Rahn *et al.*, 1946; Agostoni and Rahn, 1960) and possibly other thoracic or abdominal muscles. The mechanical properties of the connective tissue components of skeletal muscle make a major contribution to the passive length-tension behaviour of the muscle (Eisenberg, 1983). Endurance training appears to stimulate the synthesis of connective tissue components of skeletal muscle in mice (Suominen and Heikkinen, 1975a; Suominen, Kiiskinen and Heikkinen, 1980) and humans (Suominen and Heikkinen, 1975b; Suominen, Heikkinen and Parkatti, 1977). Similar adaptations in the thoraco-abdominal musculature may therefore increase the E_w.

Physical training is known to affect the physical and chemical properties of a number of connective tissues other than that found in skeletal muscle (Booth and Gould, 1975). Training-related increases in the elasticity of such tissues found within the thoracic structures, could result in an increased E_w. The costal cartilages of the sterno-costal joints are of interest in this regard, as they make a major contribution to the elasticity of the thoracic cage (Davies, 1967). However, such an effect must be considered as speculative because of the lack of directly relevant data in the literature.

ENDURANCE TRAINING AND THE WORK OF BREATHING

Mechanical Work of Breathing

Milic-Emili, Petit and Deroanne (1962) observed no difference between the $W_{m(r)}$ (per litre of ventilated gas) of highly trained and sedentary subjects, under conditions of raised minute ventilations and exercise.

However, their work measurements did not include the significant but not major, dynamic component which is expended on the thoracic structures, and therefore relate only to the dynamic work performed on the lungs. The R_1 data from Shapiro and co-workers (1964) support the idea that the dynamic W_1 (per litre of ventilation), under conditions of high airflow, is not altered by endurance training. Data from dynamic lung volume measurements also generally support this, but include inconsistencies, and are of limited value because they represent imprecise indices of the flow resistance of the small airways.

Endurance training does not appear to influence the elastic behaviour of the respiratory system as judged by the lack of change in the static lung volumes and the data from Fisher and co-workers (1970) and Leith and Bradley (1976). There is however, some indirect evidence which suggests that the E_w may be increased with some forms of endurance training. Increases in E_w and E_r will however have little, if any, effect on $W_{m(r)}$ during heavy exercise, because $W_{m(r)}$ equals the sum of the inspiratory and expiratory dynamic work components during high minute ventilations (Otis, Fenn and Rahn, 1950).

The available data are generally consistent with the view that endurance training does not significantly alter the dynamic W_1 expended per litre of ventilation during strenuous exercise. This implies that $W_{m(r)}$ (per litre of ventilation) is not altered, because the dynamic W_1 is the major component of $W_{m(r)}$ under these conditions. However, this cannot be considered as conclusive because the available data is scant, indirect, and includes inconsistencies.

Total Energy Cost of Breathing

Bradley and Leith (1978) reported that ventilatory muscle endurance training was associated with a 19% increase in the MVV_s which required a 67% increase in the $\dot{V}_{O_2 r}$, and considered these data to be "consistent with the idea that a given ventilation required the same $\dot{V}_{O_2}$ before and after training". However, these results cannot be considered as conclusive proof that such training has no effect on the W_r (per litre of ventilation). Caution must also be exercised when extrapolating these findings to training regimes which are not restricted to the respiratory musculature.

The $\dot{V}_{O_2r}$ at any given level of ventilation can only be altered by changing the $W_{m(r)}$ or RE. The limited available data suggest that endurance training does not alter the $W_{m(r)}$ (per litre of ventilation) during exercise conditions. The author is unaware of any published data concerning the effects of endurance training on the RE. However, the mechanical efficiency of exercise (i.e. the ratio of useful mechanical work performed to total energy expended) frequently shows small, but significant, increases with such training (Le Rossignol, 1982). This indirectly suggests that the RE may increase somewhat with endurance training.

EFFECTS OF ENDURANCE TRAINING ON FACTORS LIMITING ENDURANCE

Endurance may be defined as "the ability of the body to resist fatigue" (Jensen, 1978) and in healthy subjects is limited by the maximum aerobic capacity, accumulation of lactic acid in the blood, and the mechanical efficiency of exercise (Fox, 1979). The development of fatigue and exhaustion during endurance activities are also dependent on the depletion of muscle glycogen stores (Holloszy *et al.*, 1971).

Endurance training is associated with significant increases in the $\dot{V}_{O_2max}$ (Kasch *et al.*, 1973; Hickson *et al.*, 1982) and reduced blood lactic acid levels during given levels of exercise (Holloszy *et al.*, 1971; Karlsson *et al.*, 1972). Such training also reduced the utilization of muscle glycogen during given submaximal workloads (Karlsson *et al.*, 1972), in addition to raising the muscle glycogen concentration (Gollnick *et al.*, 1973). Longitudinal studies have frequently revealed a 3-8% increase in exercise efficiency following a period of endurance training (Robinson and Harmon, 1941; Karlsson *et al.*, 1972; Rasmussen *et al.*, 1975; Le Rossignol, 1982). Such an effect may reflect the development of a superior technique whereby the degree of unnecessary and wasteful muscular activity is decreased. Endurance training is associated with reductions in the minute ventilations elicited by standardized submaximal levels of exercise (Andrew *et al.*, 1966; Rasmussen *et al.*, 1975). This effect would also act to increase the exercise efficiency by reducing the $\dot{V}_{O_2r}$. Reductions in the respiratory resistances will also reduce the $\dot{V}_{O_2r}$ if the pattern and level of ventilation remain unaltered, and could therefore theoretically account for an increased exercise efficiency.

Respiratory Limitations

Pulmonary ventilation does not directly limit exercise in healthy human subjects, as the MBC is markedly higher than the minute ventilation seen during exercise at the maximum aerobic capacity (Pierce *et al.*, 1968) and expiration is little affected by effort-independent airflow maxima during near-maximal exercise (Olafsson and Hyatt, 1969). The level of ventilation above which the arterial oxygen tension falls because of the high $\dot{V}_{O_2r}$, has been estimated as equalling 120-170 $L.min^{-1}$ (Otis, 1954, 1964; Margaria *et al.*, 1960; Shephard, 1966), while the minute ventilation commonly attained during exercise at the maximum aerobic capacity equals some 120 $L.min^{-1}$ (Pierce *et al.*, 1968; Davies, Tuxworth and Young, 1970). The $\dot{V}_{O_2r}$ may therefore place a ceiling on the sustainable level of exercise in some healthy subjects.

Indirect estimates of $\dot{V}_{O_2r}$ during heavy exercise have given values ranging from 2.4 to 10% of the $\dot{V}_{O_2}$ (Margaria *et al.*, 1960: Milic-Emili, Petit and Deroanne, 1962; Otis, 1964). Such calculations have generally assumed relatively high RE values. Estimates based on lower levels of RE give sufficiently high $\dot{V}_{O_2r}$ values (up to 30% of the total $\dot{V}_{O_2}$ during heavy exercise) for the energy cost of breathing to be considered an important factor which limits the performance of strenuous aerobic exercise (Asmussen, 1965). Direct measurements of $\dot{V}_{O_2r}$ have yielded values of 10-15% of the $\dot{V}_{O_2}$ during submaximal exercise (Levison and Cherniack, 1968) and 10% during exercise at 80% of the maximum aerobic work capacity (Shephard, 1966). Variations in the body's oxygen supply which are of similar magnitude to these direct $\dot{V}_{O_2r}$ measurements, are associated with marked changes (30 to 68%) in the length of time that maximal workloads can be endured (Ekblom, Goldbarg and Gullbring, 1972; Eckblom *et al.*, 1975). It is therefore feasible that a training-related reduction in the forces opposing pulmonary ventilation, or an increase in the RE, could decrease the $\dot{V}_{O_2r}$ sufficiently to make a significant contribution to the improved performance of endurance activities which operate at or near the $\dot{V}_{O_2max}$. Such an effect could also explain the small but significant improvements in exercise efficiency which are frequently associated with endurance training.

Athletes are capable of greater levels of exertion, and display higher minute ventilations, during maximal and supramaximal workloads, than

sedentary subjects (Milic-Emili, Petit and Deroanne, 1962; Telford, Briggs and Chennels, 1978). Longitudinal studies have also revealed endurance training-related increases in the maximum minute ventilations elicited by exercise (Kasch *et al.* 1973; Magel *et al.*, 1975). However, this effect will be of little or no benefit during strenuous endurance activities because of the high $\dot{V}_{O_{2r}}$ requirements, unless it is accompanied by decreases in the $W_{m(r)}$ per litre of ventilation or increases in the RE.

CHAPTER 3

METHODOLOGICAL CONSIDERATIONS

RESPIRATORY MECHANICS MEASUREMENTS

This thesis represents a study aimed at investigating what effect, if any, endurance training has on the mechanical properties of the respiratory system and work of breathing, and whether any such changes make a significant contribution to, the improved performance of strenuous endurance activities by reducing W_r, and the training-related increases in dynamic lung volumes such as the MBC. The $W_{m(r)}$ equals the total dynamic work of breathing (inspiratory plus expiratory) at the high minute ventilations which occur during strenuous exercise or MBC manoeuvres (Otis, Fenn and Rahn, 1950). Minor changes in the E_r will therefore not significantly alter the $W_{m(r)}$ under such conditions. For the present purposes, the mechanical properties of the respiratory system would be best examined by measuring the total dynamic work of breathing, as this equals the mechanical component of W_r during high levels of ventilation and can therefore be directly compared to the $\dot{V}_{O_2 r}$.

Margaria *et al.* (1960) indirectly estimated $W_{m(r)}$ in human subjects during strenuous exercise and the associated high levels of minute ventilation. However, their method did not take into account the dynamic resistance of the thoracic structures which makes a significant contribution to R_r. Their method also assumes that intraoesophageal pressure gives a reliable index of intrapleural pressure during the high minute ventilations associated with strenuous exercise. Mead and Gaensler (1959) reported that the respiratory fluctuations in intrapleural and intraoesophageal pressures were "closely similar in configuation" during maximum voluntary ventilation, rapid shallow breathing, and slow deep breathing, but contrary observations have also been reported (Fry *et al.*, 1952; Cherniack and Proctor, 1955). These considerations make Margaria's method for measuring $W_{m(r)}$ unsuitable for the present purposes.

The total dynamic work of breathing can only be measured during conditions of artificial ventilation when respiratory muscle activity is absent. The E_r and total elastic work of breathing can also be measured

under these conditions. These parameters are influenced by the pattern and level of ventilation and should therefore be measured during the relevant conditions (i.e. strenuous exercise at or near the maximum aerobic capacity, dynamic lung volume manoeuvres). However, it is not feasible to artificially ventilate subjects during physical exertion, nor is it feasible to do so at such high minute ventilations. The mechanical respiratory work measurements must therefore be restricted to conditions of physical inactivity and moderately elevated levels of pulmonary ventilation, and the data so obtained extrapolated to the conditions of exercise and high levels of ventilation.

ANIMAL SUBJECTS AS HUMAN MODELS

Ethical considerations prevent the prerequisite subject manipulation for direct measurement of $W_{m(r)}$ (e.g. anaesthesia, muscular paralysis) in humans, so that animal subjects must be employed. However, due consideration of interspecies variation must be taken when using experimental animals as human models in physiological research. Selection of an animal model suitable for the present purposes should be confined to mammals to prevent such variations from becoming excessive. Preference is given to terrestrial species in the present case because of the difficulties associated with implementing endurance training programmes other than those based on treadmill activities. Quadrapedal mammals would be the most suitable, as they are the only mammals other than humans which walk or run. A selection is best made from those quadrapedal mammals which are commonly used in physiological research, as they are readily available, and have well established handling and maintenance procedures and a large body of relevant literature data.

Considerable interspecies variation exists in the thoracic and pulmonary morphology of mammals (McLaughlin, Tyler and Canada, 1961; Krahl, 1964) which is associated with differences in the respiratory resistances. The form of the bony thorax is determined, in part, by factors such as the species size, habitat, posture and manner of locomotion (Krahl, 1964), and the thoraco-abdominal musculature is obviously dependent on the posture and manner of locomotion.

The sheep is a quadrapedal mammal which has a thoracic-pulmonary morphology differing considerably in a number of respects to that of

humans (Anderson, 1971). However, of the mammalian quadrapeds commonly used in physiological research, the sheep has R_l and C_l values which most closely equal that found in humans (refer to Table 1.1). Data on other respiratory resistances do not appear to have been published for this species, but the C_w and C_r of a closely related species, the goat, are similar to that of humans.

From a practical viewpoint, the sheep is a suitable subject because of its:

easy availability
docile nature
low sentimental value
convenient body size for the necessary procedures and measurements (e.g. endotracheal intubation without the need for tracheostomies).

On the basis of the considerations discussed above, the sheep was selected as the most suitable species for the present purposes. However, owing to their quadrapedal nature, this species may display physiological adaptations to treadmill training which differ from that elicited in humans. Such training in the sheep may, for example, be associated with changes in the thoracic musculature and bony thorax. In this regard, treadmill training in the sheep may therefore be more closely associated to human physical activities such as swimming or oarsmanship, than running.

The ideal means of investigating the topic central to this thesis requires the measurement of $W_{m(r)}$ in humans during strenuous exercise and dynamic lung volume manoeuvres such as the MBC, but such measurements cannot be made under these conditions. The chief criticisms of the proposed methodology are the limitations imposed by using animals as human models, and the extrapolation of measurements from resting conditions to those found during strenuous exercise and dynamic lung volume manoeuvres. However, this methodology represents a feasible means of measuring $W_{m(r)}$ which has attempted to minimize these limitations. A study based on this methodology will therefore provide data which, when compared with the scant relevant data in the literature, may provide new insight into the topic central to this thesis.

CHAPTER 4

ARTIFICIAL VENTILATION OF THE CONSCIOUS SHEEP

INTRODUCTION

No practical method exists for measuring the net force applied by all the contributing respiratory muscles during spontaneous ventilation. The $W_{m(r)}$ therefore cannot be measured under these conditions (Mead and Whittenberger, 1953; Otis, 1954). However, $W_{m(r)}$ can be determined when the respiratory system is artificially ventilated because the total driving pressure can then be measured (Otis, Fenn and Rahn, 1950; Otis, 1954). Respiratory muscle activity must be abolished during such measurements so that the respirator pump performs all the work (Otis, Fenn and Rahn, 1950; Sharp *et al.*, 1964a). The use of muscular relaxants has been recommended for this purpose (Sharp *et al.*, 1964a) although deep anaesthesia has also been employed (Comroe, Nisell and Nims, 1954).

Reinhart *et al.* (1979) reported that artificial ventilation of the conscious, non-medicated sheep suppressed spontaneous ventilation. If respiratory muscle activity can be suppressed under these conditions, then the mechanical work of breathing could be determined without the need to resort to pharmacological agents. The study reported below was conducted to determine the extent to which artificial ventilation suppresses respiratory muscle activity in the conscious, non-medicated sheep.

METHODS

Six conscious, non-medicated sheep (N1-N6) were ventilated via a cuffed endotracheal tube which was inserted via a chronic tracheostomy and connected to a Palmer respiratory pump. The sheep were ventilated with two pump frequencies (26.5 and 35.5 strokes.min^{-1}) and three stroke volumes (330, 420, and 470 ml BTPS).

Air-line pressure was sensed with a pressure transducer, and was recorded with a Grass polygraph recorder during periods of pump ventilation in Sheep N1-N5. The degree of respiratory muscle activity present during periods of pump ventilation was assessed from recordings of air-line pressure. Preliminary work revealed that a pump-determined airflow-time pattern was delivered to the sheep during the expiratory stroke of

the pump (i.e. the sheep's inspiratory phase). Significant levels of phasic respiratory muscle activity would therefore alter the pattern of the air-line pressure records, so that the reproducibility of these records could be used to indicate the presence or absence of such activity.

The role of thermal tachypnoea on the suppression of respiratory muscle activity was investigated by pump-ventilating two panting sheep (N2 and N4) before and after being cooled down with cold water and a fan.

The ratio of the end-expiratory air-line pressure ($P_{end(e)}$) to the change in the air-line pressure during inspiration ($P_{end(e)}/\Delta P_i$) was calculated from the most reproducible pressure records. The multiple of this ratio and the stroke volume was calculated and used as an index for the change in EELV during periods of pump-ventilation. This calculation assumes that the respiratory muscles were relaxed and the static P-V relationship of the total respiratory system was linear over the air-line pressure range encountered. The changes in EELV were also expressed as a percentage of the eupnoeic V_T by using the V_T values reported by Hemingway and Hemingway (1966) for conscious sheep in thermoneutral conditions (V_T = 4-9 ml BTPS.kg^{-1}).

The effects of a period of pump-ventilation on alveolar P_{CO_2} (P_{ACO_2}) were examined in 3 conscious sheep (N2,3, and 6). The P_{ACO_2} was determined from end-tidal air samples collected from the air-line just distal to the endotracheal tube. Samples were collected before, and during, a 6 minute period of pump-ventilation. A stroke volume of 470 ml BTPS and a pump frequency of 35.5 strokes.min^{-1} were used for the 2 larger sheep, while a stroke volume of 380 ml BTPS was used for the smallest sheep. The CO_2 concentration of the end-tidal samples was determined by gas chromatography and expressed as P_{ACO_2} as outlined by Comroe *et al.* (1962) and corrected for a body temperature of 39 ^{0}C.

RESULTS

Suppression of respiratory muscle activity occurred more readily and to a greater extent if the sheep were in a tranquil state. An unsettled animal usually became tranquil if left undisturbed for some ten minutes with a nearby companion sheep.

Table 4.1 shows the experimental conditions and results of all attempts to pump-ventilate conscious sheep, except that related to the P_{ACO_2} study. Eructation and body movement produced distortions in the pressure traces. The former was a persistent problem in 2 sheep.

Partial suppression of respiratory muscle activity was observed during periods of pump-ventilation providing that suitable pump settings (i.e. stroke volume and pump frequency) were employed, and thermal tachypnoea was absent. The degree of this suppression was lowest in the largest sheep. Respiratory muscle activity was partially suppressed almost immediately after commencement of pump ventilation.

End-expiratory air-line pressure was always observed to be positive during periods of pump ventilation, except for movement or eructation artifacts (refer to Figure 4.1). The increase in EELV during pump ventilation was estimated to range between 57 and 235 ml BTPS (mean 135 ml). This increase constitutes 15 to 159% of the eupnoeic V_T with a mean increase of 35 to 79% (refer to Table 4.2).

Table 4.3 shows the effects of a 6 minute period of pump ventilation on the P_{ACO_2} and shows decreases in 2 of the 3 sheep examined. Artificial ventilation had to be aborted after 4 minutes in sheep N2 because of persistent coughing.

DISCUSSION

Reinhart *et al.* (1979) artificially ventilated conscious sheep with oxygen to determine the distribution of ventilation by multiple-breath nitrogen washout. These workers ventilated sheep at a rate of 30 strokes. min^{-1}, a fixed stroke volume of 400 ml, and an inspiratory to expiratory time ratio ($T_i:T_e$) of 1:1, and noted that spontaneous ventilation was suppressed under these conditions. Similar results were obtained by these workers when a stroke volume of 350 ml was employed (Ahmed *et al.*, 1980). The results of the present study support these findings and demonstrate that room air may be used as the ventilating gas. The latter observation is consistent with reports that normoxic subjects display little ventilatory depression when made hyperoxic by raising the inspired oxygen concentration (Dripps and Comroe, 1947; Honda and Kreuzer, 1966).

Table 4.1 Summary of experimental conditions and results of attempts to artificially ventilate conscious tranquil sheep

Sheep N1 - shorn, body-weight 80.5 kg, air temperature 24.0-26.5°C										
f_r †	NT	NT	NT							
Stroke volume	420 ml	470 ml	470 ml							
Stroke frequency	26.5.min^{-1}	35.5.min^{-1}	35.5.min^{-1}							
Respiratory activity+	marked	marked	moderate							
Sheep N2 - unshorn, body-weight 52.4 kg, air temperature 23.0-24.5°C										
f_r	T	T	T	T	NT*	NT	NT	NT	NT	NT
Stroke volume	330 ml	470 ml	330 ml	470 ml	330 ml	470 ml	330 ml	470 ml	330 ml	470 ml
Stroke frequency	26.5.min^{-1}	26.5.min^{-1}	35.5.min^{-1}	35.5.min^{-1}	26.5.min^{-1}	26.5.min^{-1}	26.5.min^{-1}	26.5.min^{-1}	35.5.min^{-1}	35.5.min^{-1}
Respiratory activity	marked	marked	marked	marked	marked	slight	moderate	slight	slight	slight
Sheep N3 - shorn, body-weight 59.4 kg, air temperature 23.0-25.0°C										
f_r	NT	NT	NT	NT						
Stroke volume	470 ml	470 ml	420 ml	470 ml						
Stroke frequency	35.5.min^{-1}	35.5.min^{-1}	26.5.min^{-1}	35.5.min^{-1}						
Respiratory activity	slight	slight	slight	slight						
Sheep N4 - unshorn, body-weight 31.6 kg, air temperature 23.0-25.0°C										
f_r	T	T	T	T	NT*	NT	NT	NT	NT	
Stroke volume	330 ml	470 ml	330 ml	470 ml	330 ml	470 ml	330 ml	330 ml	470 ml	
Stroke frequency	26.5.min^{-1}	26.5.min^{-1}	35.5.min^{-1}	35.5.min^{-1}	26.5.min^{-1}	26.5.min^{-1}	26.5.min^{-1}	35.5.min^{-1}	35.5.min^{-1}	
Respiratory activity	marked	marked	marked	marked	moderate	slight	slight	slight	slight	
Sheep N5 - unshorn, body-weight 37.0 kg, air temperature 22.0-24.0°C										
f_r	NT	NT	NT	NT	NT	NT	NT			
Stroke volume	330 ml	330 ml	470 ml	330 ml	470 ml	330 ml	470 ml			
Stroke frequency	26.5.min^{-1}	26.5.min^{-1}	26.5.min^{-1}	26.5.min^{-1}	26.5.min^{-1}	35.5.min^{-1}	35.5.min^{-1}			
Respiratory activity	moderate	moderate	slight	slight	slight	slight	slight			

† sheep's respiratory frequency immediately before attempt to pump-ventilate; NT not tachypnoeic (f_r < 30 breaths.min^{-1}), T tachypnoeic (f_r > 100 breaths.min^{-1})

* sheep cooled down with cold water and a fan

\+ degree of respiratory muscle activity during periods of pump ventilation as assessed from air-line pressure records

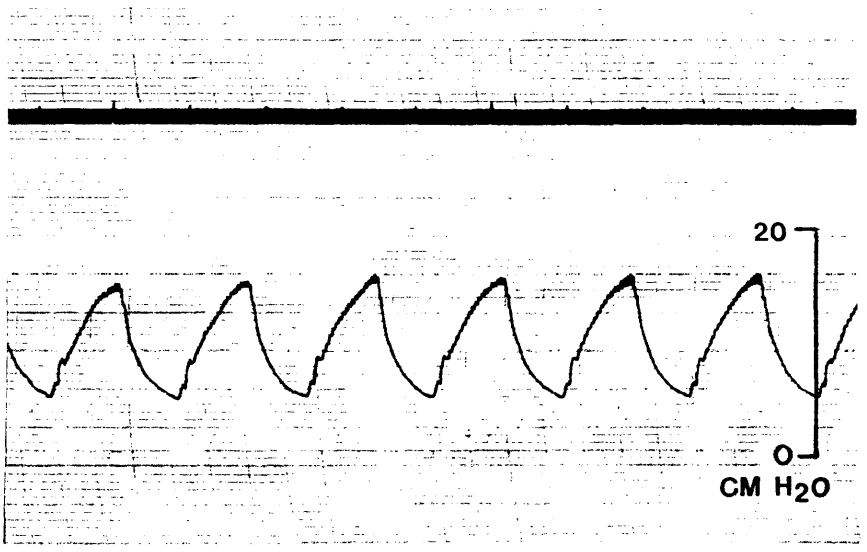

Fig. 4.1 Time (1 second divisions) and air-line pressure records from a successfully pump-ventilated sheep

Table 4.2 Estimated change in end-expiratory lung volume during periods of pump ventilation

Sheep	Stroke frequency (strokes.min^{-1})	Stroke volume (ml BTPS)	Change in EELV (ml BTPS)	Change in EELV (% of eupnoeic V_T)
N2	26.5	470	104	22-50
N2	26.5	470	97	21-46
N2	26.5	330	69	15-33
N2	35.5	330	106	22-50
N2	35.5	470	165	35-79
N3	35.5	470	235	44-99
N3	35.5	470	223	42-94
N3	35.5	470	215	40-90
N4	26.5	470	82	29-65
N4	26.5	330	57	20-45
N4	35.5	330	91	32-72
N4	35.5	470	176	62-140
N5	26.5	330	93	28-63
N5	26.5	330	92	28-62
N5	26.5	330	104	31-70
N5	26.5	470	157	47-106
N5	26.5	330	110	33-74
N5	26.5	470	145	44-98
N5	35.5	330	139	42-94
N5	35.5	470	235	71-159
		Mean	135	35-79
		Range	57-235	15-159

Note: Changes in EELV were always increases

Table 4.3 P_{ACO_2} of 3 sheep, before and during a period of pump ventilation

Time	End-tidal P_{CO_2} (mmHg) Sheep N2	Sheep N3	Sheep N6	Mean
before [+]	32	27	31	30
¼ min	29	25	29	28
½ min	28	24	26	26
1 min	31	25	30	29
2 min	29	23	27	26
4 min	23	20	30	24
6 min	-[*]	23	30	27

[+] Samples taken 1 to 3 minutes before commencement of pump ventilation. The remaining values in the time column denote the duration of pump ventilation when samples were taken.

[*] Pump ventilation had to be aborted after 4 minutes because of persistent coughing.

Suppression of respiratory muscle activity was never complete, and was not observed if the respiratory drive was raised during thermal tachypnoea. Animal cooperation was essential because body movement affected the air-line pressure records, as did eructation. Although thermal tachypnoea could be readily abolished by cooling down the sheep (refer to Table 4.1), animal cooperation could not be guaranteed. The pump-ventilated conscious sheep therefore cannot be considered suitable for the measurement of $W_{m(r)}$.

Two factors may have contributed to the reduction in respiratory muscle activity during artificial ventilation. These are the reflex inspiratory apnoea associated with lung inflation, and the reduced respiratory drive associated with hypocapnia.

When suppression of respiratory muscle activity occurred, it did so almost immediately after commencement of pump ventilation, indicating that the suppression occurred via a reflex pathway. Maintained lung inflation increases the duration of the subsequent expiratory phase in many mammalian species by a vagal-mediated reflex, the Hering-Breuer inflation reflex (Widdicombe, 1961; Chapman, Santiago and Edelman, 1982).

The consistent failure of the air-line pressure to fall to zero at end-expiration strongly indicates that the EELV was raised during periods of pump ventilation. This effect occurs during artificial ventilation when the net elastic recoil of the inflated respiratory system is insufficient to deflate the lungs to the relaxation volume during T_e (Peters, 1969). The Hering-Breuer inflation reflex may therefore have been continuously stimulated by the raised EELV during artificial ventilation, and further stimulated during each inspiration, resulting in a suppression of inspiratory muscle activity. As the expiratory phase appears to be passive during eupnoeic conditions except for some carry-over of inspiratory activity (Campbell, 1958; Green and Howell, 1959; Petit, Milic-Emili and Delhez, 1960), all respiratory muscle activity would be suppressed.

Administration of constant positive airway pressure to conscious sheep produces a period of apnoea (Kung, Reinhart and Wanner, 1978), indicating that the Hering-Breuer inflation reflex can be evoked in this species. Approximations of the change in EELV during periods of pump ventilation in the present study indicate a mean increase of 35 to 79%

of the eupnoeic V_T, with a range of 15 to 159% (refer to Table 4.2). If the observed suppression of respiratory muscle activity can be accounted for by the proposed mechanism, then the Hering-Breuer inflation reflex would have to be evoked by increases in the EELV which often comprised only a fraction of the eupnoeic V_T. Vagotomy or vagal tying results in increases in V_T and decreases in f_r in anaesthetized sheep (Rangsit, 1941; Colebatch and Halmagyi, 1963), indicating that the Hering-Breuer inflation reflex is active over the eupnoeic V_T in this species (Widdicombe, 1964; Phillipson *et al.*, 1970; Chapman, Santiago and Edelman, 1982). Caution must be exercised when extrapolating these findings to the conscious sheep however, as anaesthesia augments this reflex in some species (Widdicombe, 1961; Bouverot, Crance and Dejours, 1970).

The extent of pulmonary stretch receptor activity is directly related to the degree by which the lungs are stretched (Guz and Trenchard, 1971), a factor which is dependent on both lung volume and body size. The poor degree of suppression of respiratory muscle activity observed in the largest sheep (N1) may therefore have occurred because the pump settings were insufficient to increase the EELV enough to adequately stimulate these receptors. Furthermore, the possibility exists that complete suppression may result if sufficiently high pump settings are employed.

A 4 to 6 minute period of pump ventilation decreased the P_{ACO_2} in 2 of the 3 sheep examined (refer to Table 4.3). Reinhart *et al.* (1979) found the arterial CO_2 tension (P_{aCO_2}) of 2 conscious sheep to be 30 and 35 mm Hg after a period of pump ventilation. These workers examined sheep of lower body weight and employed somewhat lower pump settings to that of the present study, and did not state the exact duration of the period of pump ventilation or report control P_{aCO_2} measurements. One therefore cannot directly compare their data with that from the present study, although the baseline values reported by these workers in other studies (Wanner *et al.*, 1979; Kung *et al.*, 1980) indicate that pump ventilation did not markedly decrease P_{aCO_2}.

Reducing the humoral drive to respiration by artificial hyperventilation, results in a progressive decrease in respiratory motor neurone and muscle activity (Bronk and Ferguson, 1935; von Euler and Fritts, 1963). Furthermore, the duration of reflex inspiratory apnoea evoked by maintained

lung inflation is decreased during hypercapnia (Bouverot, Crance and Dejours, 1970; Younes, Vaillancourt and Milic-Emili, 1974). In view of this, it is likely that under the experimental conditions of the present study, hypocapnic apnoea while not immediately apparent, would contribute progressively to the suppression of respiratory muscle activity. This was not obvious from the data however, perhaps because the sheep were rarely pump-ventilated for longer than 3 minutes.

Respiratory muscle activity was never completely suppressed, and the extent of this activity may have been underestimated as artificial ventilation can bring such activity into phase with the pump (Adrian, 1933; Comroe, Nissel and Nims, 1954). It is not possible to determine from the data whether tonic respiratory muscle activity was present. Many electromyographic studies on conscious eupnoeic subjects have consistently revealed a lack of respiratory activity at end-expiration (Green and Howell, 1959; Agostoni, Sant'Ambrogio and Del Portillo Carrasco, 1960; Petit, Milic-Emili and Delhez, 1960). However, more recent studies have reported the presence of tonic diaphragmatic and intercostal muscle activity during eupnoeic ventilation (Muller *et al.*, 1979; Lopes *et al.*, 1981; Tabachnik *et al.*, 1981). The presence of such activity in the pump-ventilated sheep of the present study therefore cannot be excluded.

CONCLUSION

This study confirms the findings by Reinhart *et al.* (1979) that under suitable conditions, conscious, non-medicated sheep can be artificially ventilated with a resultant suppression of respiratory muscle activity. However, such suppression was never complete. The problems associated with animal cooperation and eructation, in addition to the incomplete suppression of respiratory muscle activity, makes the pump-ventilated, conscious, and non-medicated sheep unsuitable for the measurements of respiratory work central to this thesis.

The suppression of respiratory muscle activity appears to be reflex in nature. A possible mechanism which is consistent with the data is the continuous stimulation of the Hering-Breuer inflation reflex resulting from a maintained increase in the EELV. After a time, the reflex apnoea may be augmented by the progressive development of hypocapnia.