

The variability of cardiopulmonary adaptation to pregnancy at rest and during exercise

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Abbreviations

[According to Tammerling (1983)]

Abbreviations

ATPS	ambient temperature and barometric pressure, saturated with water
BTPS	body temperature, standard barometric pressure, saturated with water
$cAco_2$	alveolar carbon dioxide content (ml/l)
$caco_2$	carbon dioxide content of the arterial blood (ml/l)
$c\ co_2$	carbon dioxide content (ml/l)
$c\bar{v}co_2$	carbon dioxide content of the mixed venous blood (ml/l)
Δ	delta or difference
FeO_2	fraction of expiratory oxygen (%)
FiO_2	fraction of inspiratory oxygen (%)
f_C	cardiac frequency (beats/min) (b.p.m.)
f_R	breathing frequency (breaths/min)
$c\ o_2$	oxygen content (ml/l)
$PAco_2$	alveolar carbon dioxide pressure (kPa) (mmHg)
$Paco_2$	arterial carbon dioxide pressure (kPa) (mmHg)
$P\bar{v}co_2$	mixed venous carbon dioxide pressure (kPa) (mmHg)
\dot{Q}	cardiac output (l/min)
R	respiratory exchange ratio
RQ	respiratory quotient
STPD	standard temperature and pressure, dry
$tcPco_2$	transcutaneous carbon dioxide pressure (kPa) (mmHg)
$tcPo_2$	transcutaneous oxygen pressure (kPa) (mmHg)
\dot{V}	ventilation per time unit (l/min)
\dot{V}_A	alveolar ventilation per time unit (l/min)
$\dot{V}co_2$	carbon dioxide production per time unit (ml/min)
$\dot{V}o_2$	oxygen consumption per time unit (ml/min)
$\dot{V}o_2/f_C$	oxygen consumption per heart beat (ml)
V_T	tidal volume (ml)
$\dot{V}/\dot{V}co_2$	ventilation equivalent for carbon dioxide
$\dot{V}/\dot{V}o_2$	ventilation equivalent for oxygen

Methods and principles

Infrared spectrophotometry
Calculated from expiratory $c\ co_2$ (end-tidal $c\ co_2$)
Infrared spectrophotometry
Rebreathing method (Campbell & Howell 1962)
Paramagnetic analysis
Paramagnetic analysis
ECG
Pneumotachograph (Fleisch)
Paramagnetic analysis
Calculated from end-expiratory $c\ co_2$
Rebreathing method (Campbell & Howell 1962)
Indirect Fick principle
$\dot{V}co_2/(c\bar{v}co_2 - cAco_2)$
$\dot{V}co_2/\dot{V}o_2$
$\dot{V}co_2/\dot{V}o_2$ at rest
Heated skin CO_2 electrode
Heated skin O_2 electrode
Pneumotachograph
$\dot{V}co_2/cAco_2$
$c\ co_2 \times \dot{V}$
$c\ o_2 \times \dot{V}$
$c\ o_2 \times \dot{V}/f_C$
\dot{V}/f_R

Abstract

Objective To examine the cardiopulmonary adaptation to normal pregnancy in sitting women during rest and bicycle exercise.

Design A longitudinal study beginning early in pregnancy and ending 8-12 months after delivery.

Setting University Hospital, Zurich, Switzerland.

Subjects 20 women were monitored every second week during pregnancy from 8 to 14 weeks gestation, twice in the puerperium and twice 6-8 weeks and twice 8-12 months after delivery. All the women finished the study, but not all of them participated in every visit.

Measurements and main results

The results obtained 8-12 months after delivery are considered the non-pregnant data and are presented first so that any change in pregnancy will be more obvious. Values given below refer to the median except when stated otherwise.

At rest

1. Oxygen consumption increased significantly from a median of 182 ml/min in the non-pregnant state to 256 ml/min by 8-11 weeks gestation, and peaked at 300 ml/min at 32 weeks. At 6-8 weeks after delivery the value was 225 ml/min.
2. Oxygen consumption per kg increased significantly from 3.0 ml/min in the non-pregnant state to 4.3 ml/min by 8-11 weeks gestation and peaked at 5.0 ml/min soon after delivery. At 6-8 weeks after delivery the value was 3.4 ml/min.
3. Carbon dioxide production generally showed changes similar to those of oxygen consumption.
4. Respiratory quotient did not show any significant changes.
5. Ventilation increased from a median of 9.4 l/min in the non-pregnant state to 10.5 l/min by 8-11 weeks and then slowly increased to 12.6 l/min in late pregnancy.
6. Respiratory rate did not change significantly.
7. Tidal volume showed a median of 563 ml in the non-pregnant women and rose significantly to 632 ml in early pregnancy, peaking at 715 ml in late pregnancy.
8. Alveolar ventilation increased significantly from a non-pregnant value of 3.4 l/min to 6.2 l/min in early pregnancy, peaking at 6.7 l/min at term; 6-8 weeks after delivery the value was 4.5 l/min.
9. Ventilation equivalent for oxygen fell significantly from the median non-pregnant value of 52 to 42 in early pregnancy and remained at that level until 6-8 weeks after delivery when it was 44.
10. Ventilation equivalent for carbon dioxide showed similar changes to those for oxygen.
11. Alveolar carbon dioxide tension fell significantly from a median non-pregnant level of 4.6 kPa (34 mmHg) to 4.0 kPa

(30 mmHg) in early pregnancy. It began to increase in the puerperium and was 4.3 kPa (33 mmHg) 6-8 weeks after delivery.

12. Mixed venous carbon dioxide tension fell significantly from a median of 5.9 kPa (44 mmHg) to 5.2 kPa (39 mmHg) during pregnancy.

13. Transcutaneous carbon dioxide tension decreased significantly in early pregnancy from 8.8 kPa (66 mmHg) in the non-pregnant women, and from 20 weeks gestation remained at 6.9 kPa (52 mmHg).

14. Transcutaneous oxygen tension showed a non-significant increase from 10.0 kPa (75 mmHg) in the non-pregnant women to 11.1 kPa (83 mmHg) during pregnancy.

15. Cardiac frequency increased gradually from a non-pregnant median of 80 b.p.m. to about 90 b.p.m. in the last 2 months of pregnancy. In the puerperium the median was 75 b.p.m.

16. Cardiac output increased significantly by almost 50% from the non-pregnancy level to that at 8-11 weeks gestation.

17. Cardiac output per kg also increased significantly by 50% from the non-pregnant level to that at 8-11 weeks gestation. From mid-pregnancy there was a gradual fall until delivery.

18. Stroke volume increased significantly from a median of 31 ml in the non-pregnant state to 51 ml in early pregnancy, and remained at this level until delivery. In the puerperium the stroke volume was 63 ml.

19. Oxygen pulse increased significantly from a median of 2.2 ml in the non-pregnant women to 3.1 ml in early pregnancy and remained at that level.

20. Individual curves. For some of the variables studied, individual patterns of change were very similar and there was minimal crossing of the individual lines during the whole period of observation. This applied to weight, alveolar ventilation, alveolar carbon dioxide tension, mixed venous carbon dioxide tension and cardiac output/kg. Oxygen consumption, carbon dioxide production, ventilation, respiratory rate, tidal volume, ventilation equivalents for oxygen and for carbon dioxide, heart rate, cardiac output and oxygen pulse were generally more or less parallel, but many women had peak or nadir

values at different times. Finally, oxygen consumption/kg, transcutaneous carbon dioxide and oxygen tension and stroke volume varied markedly between individual women.

During bicycle exercise

In order not to obfuscate the changes due to exercise with those of pregnancy *per se*, the results during exercise are given as $\Delta\dot{V}_{O_2} = \dot{V}_{O_2} \text{ work} - \dot{V}_{O_2} \text{ rest}$ (\dot{V}_{O_2} = oxygen consumption).

21. Δ Oxygen consumption increased significantly during moderate work at 8–11 weeks gestation, then fell slightly and peaked in late pregnancy.

22. Δ Carbon dioxide production showed similar changes to that of oxygen.

23. Δ Ventilation increased significantly by 8–11 weeks gestation and plateaued at a higher value at 12–15 weeks.

24. Δ Respiratory rate showed no significant changes attributable to pregnancy.

25. Δ Tidal volume increased significantly by 8–11 weeks gestation and then decreased to the non-pregnant value by late pregnancy.

26. Δ Alveolar ventilation increased significantly by 8–11 weeks gestation and remained at a plateau until delivery.

27. Δ Heart rate increased significantly at 12–15 weeks gestation but fell below that in the non-pregnant woman in the last 2 months of pregnancy.

28. Δ Oxygen pulse increased significantly by 8–11 weeks gestation and then fell to the non-pregnant value except in the last 2 months of pregnancy.

29. Work efficiency was 25% during moderate work in the

non-pregnant women. The value was significantly lower at 8–11 weeks gestation and then decreased gradually to 20% in late pregnancy. During light work, efficiency was 20% in the non-pregnant women and fell parallel to the curve associated with moderate work.

30. Individual curves tended to follow the same pattern for oxygen consumption, carbon dioxide production, ventilation, alveolar ventilation, heart rate, oxygen pulse and work efficiency. Respiratory rate and tidal volume varied markedly from woman to woman.

Conclusions

1. Most of the cardiopulmonary variables studied had already changed significantly by 8–11 weeks gestation both at rest and during exercise.

2. Six to eight weeks after delivery the basic non-pregnant levels were not yet achieved. Thus, the changes described by several authors who considered 6–8 weeks after delivery as the non-pregnant level will be smaller than the true ones.

3. The controversy about adaptation to pregnancy may partly be explained by varied individual responses.

4. The reduced work efficiency during pregnancy contributes to the limitation of reserves needed for exercise.

5. None of the variables studied during exercise pointed clearly to a risk for maternal or fetal oxygenation. However, the lack of optimal maternal heart rate increase during the last months of pregnancy indicates that the oxygen supply to the working muscles is given preference to the visceral circulation, perhaps including the uterus. This point needs further investigation.

1. Introduction

It would seem that after the detailed treatment by various authors (Hyttén & Chamberlain 1980; Lotgering *et al.* 1985; Artal & Wiswell 1986) this subject would be adequately covered. However, it suffices to quote the last named authors (Artal & Wiswell 1986): 'Since 1915 basic work has been compiled to understand the pregnant woman's physiological alterations at rest and during exercise. Much of the knowledge on exercise is limited and some is contradictory. Thus, the impact of exercise on pregnancy is open for further investigation.'

Whereas most authors agree on some trends, such as reduced maternal P_{CO_2} during pregnancy, increased maternal oxygen consumption and carbon dioxide production, and increased ventilation, even these regular patterns may not be present in every woman. The earliest studies usually included only a few pregnant women and the individual data were presented in tables. A typical example of this is the work of Anthony & Hansen (1934) who also reviewed the earliest literature on this subject. In one of their 14 women, $\dot{V}O_2$ was virtually the same before and after delivery, whereas carbon dioxide production ($\dot{V}CO_2$) was higher after delivery. The

authors do not refer to this as they are interested in observing the general trends. Pernoll *et al.* (1975) were amongst the first to provide some tabulated values and indicate the number of cases conforming with the general pattern.

The object of this longitudinal study was to describe the general pattern of pulmonary and cardiovascular changes in pregnancy in sitting women at rest and during exercise, emphasizing the individual variation.

The chief objective of the perinatal physiological research unit at the Department of Obstetrics in University Hospital, Zurich, has been and remains the study of the physiological reactions of the pregnant woman, the fetus and the newborn infant using non-invasive techniques. Without a proper knowledge of the normal adaptation, no accurate assessment of pathological events is possible except when the changes are very pronounced. The recent availability of combined equipment for the study of ventilation, oxygen consumption, etc. allows one to study pregnant women with less associated discomfort than before, and computer analyses at different stages of the study allow the handling of large data sets.

2. Subjects and methods

2.1 Participants

Permission for the study was obtained from the ethics committee of the department. The study was carefully described to the participating pregnant women who all gave their informed consent. Routine clinical care was always carried out at the end of the tests.

There was no bias in the selection of the participating women except on purely practical grounds, that is, they had to have the time and the motivation to attend for investigations every fortnight during pregnancy. If at the first antenatal clinic visit at the department the duty doctor considered the woman a possible candidate, she was approached and, if willing, she was referred to the person (L.S.) responsible for running the tests. The study was then explained in detail and, if the woman agreed, she became a participant.

Only apparently healthy women were chosen, although one was only 17 years of age, short and thin, another was obese, and one primigravida was 36 years of age. All said that they did not smoke. Three women were temporarily admitted to hospital because of suspected preterm labour; during this time they performed no exercise tests but some studies were made at rest. One woman was delivered at 35 weeks gestation, all the others at term (Table 1, see p. 6). All the infants were healthy.

Several women did not attend for the tests at different times and for different reasons. Some entered the study only at 12-15 weeks gestation, some could not come because of colds, sick infants at home, etc. Occasionally one of the monitors failed. Four of the women had left Switzerland by 8-12 months after delivery when the non-pregnant values were obtained. The number of women studied is given in each figure.

2.2 Experimental design

The women entered the study after their first visit to the antenatal clinic of the department. As only very few entered before 8 weeks gestation, data are only given from this time. The women were seen every second week and the resting values were obtained. The exercise studies were performed at two levels of workload and were made at every second visit to the laboratory, i.e. once a month. The studies at rest were repeated twice in the early puerperium, at 6-8 weeks after delivery (only referred to as 6 weeks) and again at 8-12 months post partum. The latter value is considered to represent the non-pregnant state and for this reason is shown as the first point of the measurements. Of the two measurements at rest obtained during the puerperium the mean value is given in the figures. Depending upon which day of the week the delivery took place, the first test was on the first to third day after delivery and the second test on the fourth to seventh day. The mean of these two results was used to give the most representative background for the exercise results. The exercise test was performed as often in conjunction with the first as with the second examination in the puerperium.

The tests were always performed at the same time each day, either at 09.00 or 14.00 hours after the woman had had breakfast or lunch, respectively. After a rest period the different leads were connected. The woman then sat down on the bicycle and the face mask was attached. Thus all the tests were made when the woman was in an upright sitting position. First mixed venous carbon dioxide pressure ($Pvco_2$) was measured, thereafter gas exchange, minute volume, heart rate and maternal blood pressure at rest. The following protocol was used:

- a. 5 min rest
- b. 6 min light work
- c. 5 min rest
- d. 6 min moderate work
- e. 10 min rest

The workload was selected for each woman taking account of her size and condition. The aim was to obtain a heart rate of about 130 b.p.m. during the moderate work and the workload was then halved for the light work. In practice, moderate work was usually 60 W and light work 30 W. There were some exceptions in eight women. In six of them moderate work was reduced to 50 W from mid-gestation because they could not tolerate working at 60 W, in one woman the moderate workload was always 40 W, and in the other it was always 70 W. For brevity the terms 'light' and 'medium' work will be used. When workloads other than 30 and 60 W were given and this affected the result, this is mentioned.

In the results the data have been grouped in 4-week intervals. When the same woman was monitored twice during this period the mean value is used.

The same doctor and the same technician attended every test.

2.3 Measurements

Except for fetal heart rate monitoring before and after exercise with a Hewlett-Packard cardiocograph 8040A with auto-correlation, all measurements were made on the woman.

Gas exchange and ventilation at rest and during exercise were monitored with the Ergostar (R) (Fenyves & Gut, Basle, Switzerland). This combines a heated Fleisch pneumotachograph, an infrared CO_2 analyser (Binos, Leybold Heraeus, Hanau, Germany), a paramagnetic oxygen analyser (Sybron, Tayler Ltd, Crowborough, Sussex, UK) and suitable computer equipment. A lead from the ECG equipment gave heart rate. This as well as f_R , \dot{V} , $\dot{V}O_2$, $\dot{V}CO_2$ and \dot{Q} were printed out every 30 s. The first four outputs during the initial rest period were deleted as they showed a lack of steady-state levels. $P\bar{v}CO_2$ was only obtained during rest. Consequently this also holds for cardiac output and stroke volume.

A two-point calibration of the pneumotachograph with a precision pump was performed before every test (Fenyves & Gut).

Lung volumes were recalculated to BTPS by the Ergostar. The error of these measurements was less than 2%. The infrared CO₂ analyser was calibrated with two known gases before each test. The oxygen analyser was calibrated with air after each CO₂ calibration.

A bicycle ergometer (Siemens-Elma, Solna, Sweden) was adapted so that the pregnant women could lean slightly backwards, and it could be adjusted for individual height so that the women were comfortable. Within a certain range the workload was independent of the rate of pedalling. The women were encouraged to keep a speed of 60 revolutions/min.

Transcutaneous oxygen and carbon dioxide pressure was obtained with the Transoxode and Transcapnode (Dräger, Lübeck, Germany).

Fetal heart rate, maternal blood pressure, haematocrit, haemoglobin, progesterone, oestradiol, oestriol, and human placental lactogen concentrations as well as uterine contractions were monitored in order to safeguard the fetal and maternal wellbeing. These measurements were not part of the cardiopulmonary study but some of the results have been used in the discussion for the interpretation of the main results. None of these measurements indicated fetal or maternal stress caused by the study.

In illustrating the results obtained in the pregnant women at rest, before the exercise, a modified so-called multiple 'box and whisker' plot (as shown in Fig. 3.1) has been utilized (McGill *et al.* 1978). The upper and lower limits of the boxes

display the 25th and 75th centiles, the line in between is the median, and the mean value is marked with a star. The lower whisker indicates the lowest value observed within one box length below the box, and the corresponding upper whisker is analogous. Where a value lies outside the whisker, the extreme value is marked by a diamond. In this study reference has mainly been made to the median values. This presentation contains in itself statistical information of the individual variability, in the level and the trend of the curves. Usually on the right side of each such illustration is a figure showing the individual changes. Here, for the sake of clarity, values are plotted only for the non-pregnant, and 8-11, 20-23 and 36-40 weeks gestation.

In most of the 'box and whisker' plots there was no Gaussian distribution; the median and the mean did not coincide, and the median was not equidistant from the 25th and the 75th centiles. The statistical differences between the median values were tested using the Wilcoxon paired test ($P \leq 0.05$ was considered significant). Any significant differences between the non-pregnant and the pregnant medians are indicated and also the stage of the pregnancy at which this first occurred. A summary of the statistical results is shown in Tables 3 and 4 (pp. 21 and 36).

In some of the illustrations, perhaps seen most clearly in the cardiac output, the number of women studied in the 'box and whisker' plot was higher than the individual women illustrated. This is because a line was only drawn when the connected time periods were available.

3. Results

3.1 Maternal weight

As so many of the cardiopulmonary variables are a function of weight, the maternal weight changes during pregnancy were recorded (presented in Fig. 3.1). The median maternal weight only began to increase in mid-pregnancy and peaked in the last month. Compared with the non-pregnant median the increase was statistically significant by 20-23 weeks gestation. Delivery resulted in a median maternal weight loss of 7 kg, and in the following 6 weeks there was a further median weight loss of 4 kg.

Table 1 and Fig. 3.2 illustrate the weights of the women in the study. Although the absolute weight changes differed, the graphs show that, on the whole, the relative changes were similar, as the lines only cross occasionally. As the inter-individual weights varied by a factor of two, it is clear that at least those variables that were most influenced by weight

should be standardized for weight. The mean weight increase was 12 kg, although it may be more informative to state that the mean weight increase during pregnancy was 17%.

3.2 Oxygen consumption

Figure 3.3 shows that there was a distinct and significant rise of 40% in median $\dot{V}O_2$ from the non-pregnant level of 182 ml/min to 256 ml/min by 8-11 weeks gestation. Thereafter there was a more gradual increase until 32 weeks gestation. In the puerperium, $\dot{V}O_2$ was maintained at the pregnant level but had fallen markedly by 6-8 weeks after delivery to 223 ml/min. Thus at this stage $\dot{V}O_2$ was more or less midway between the non-pregnant and the 8-11 weeks value.

There was a wide distribution of the results within each time period. Also, as seen in Fig. 3.4, the individual peak could occur early, at mid-pregnancy or at term. The different levels

Table 1. Characteristics of the women recruited to the study

No.	Age at delivery (years)	Parity	Height (cm)	Maternal weight (kg)		Gestation (weeks)		Birth weight (g)
				At entry	At delivery	At entry	At delivery	
1	28	1	168	64	71	12	40	3780
2	29	1	164	53	60	5	39	2800
3	24	1	172	53	67	7	40	4010
4	38	2	163	70	79	11	41	3980
5	23	1	160	63	65	10	39	3140
6	35	2	165	58	74	8	40	3300
7	28	2	162	53	62	11	41	4240
8	27	2	170	60	73	9	41	3900
9	22	1	160	71	82	9	37	2900
10	26	1	163	51	63	9	41	3300
11	30	1	165	63	72	9	39	3200
12	18	1	154	42	50	6	35	1930
13	31	3	166	64	73	7	40	3300
14	21	1	165	60	71	7	38	2600
15	30	2	158	47	55	8	39	3300
16	36	1	170	86	98	8	42	4300
17	24	2	165	63	73	7	38	2700
18	35	1	163	55	63	14	41	3950
19	28	1	159	53	64	10	38	3040
20	28	1	165	58	74	6	39	3400
Median	28	1	165	59	71	9	40.5	3300
Min.	18	1	154	42	50	7	35	1930
Max.	38	3	172	86	98	14	42	4300

Clinical details for subject nos:

1. Hospitalized at 31 weeks because of early strong contractions. Intravenous tocolysis for 15 days.
2. Hospitalized at 25 weeks because of early onset of labour. No further studies until the puerperium.
8. Caesarean section because of narrow pelvic outlet.
11. Hospitalized at 27 weeks because of early onset of labour. No further studies until the puerperium.
12. Caesarean section because of lack of progress in labour.
17. Forceps delivery because of lack of progress in labour.
19. Cervical insufficiency at 17 weeks. Cerclage at 20 weeks. No further studies until the puerperium.

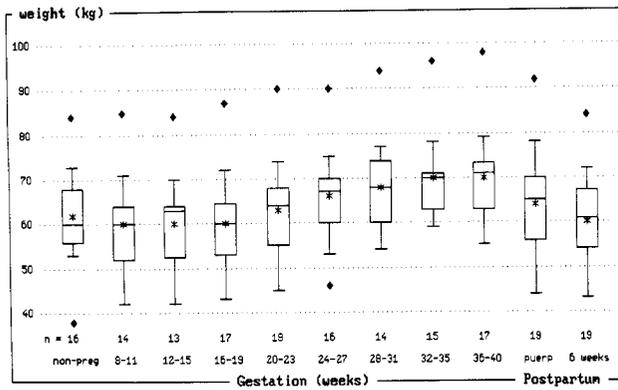


Fig. 3.1. 'Box and whisker' plot of maternal weight. The median is marked with a bar in the box, the mean with a star. The lower box border is the 25th centile and the upper one the 75th centile. The whiskers are the highest and the lowest values found within one additional box. Values outside this are marked with a diamond.

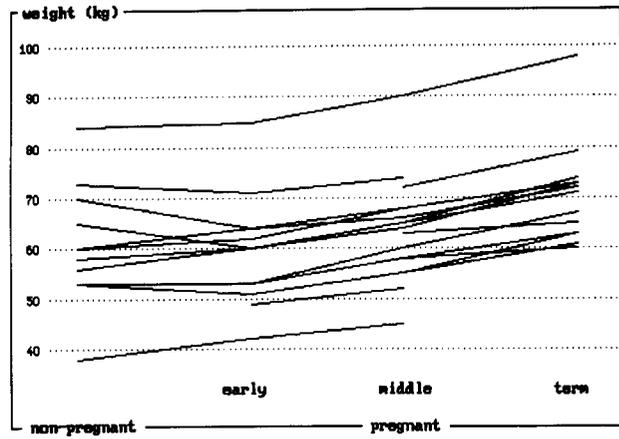


Fig. 3.2. Individual weight curves.

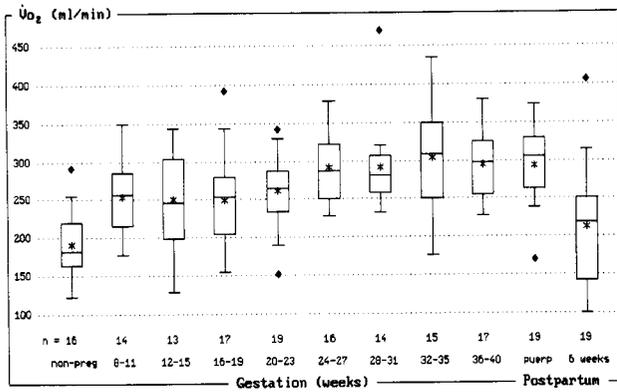


Fig. 3.3. 'Box and whisker' plot of oxygen consumption ($\dot{V}O_2$).

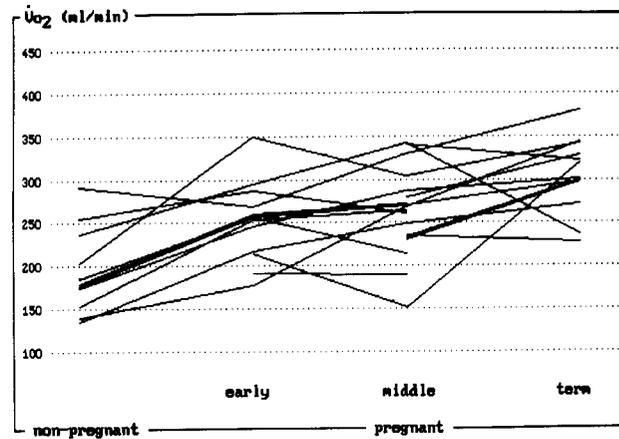


Fig. 3.4. Individual curves for oxygen consumption.

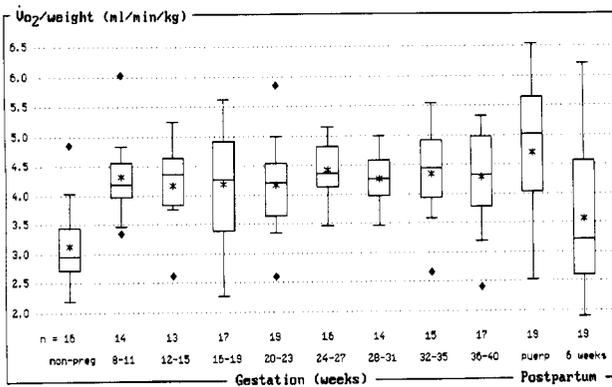


Fig. 3.5. 'Box and whisker' plot of oxygen consumption per kg of weight.

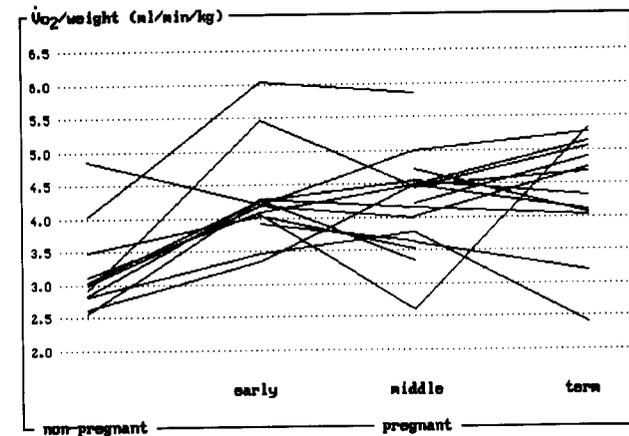


Fig. 3.6. Individual curves for oxygen consumption per kg of weight.

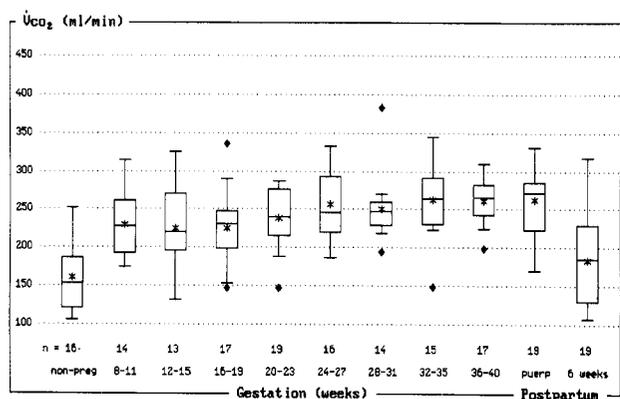


Fig. 3.7. 'Box and whisker' plot of carbon dioxide production.

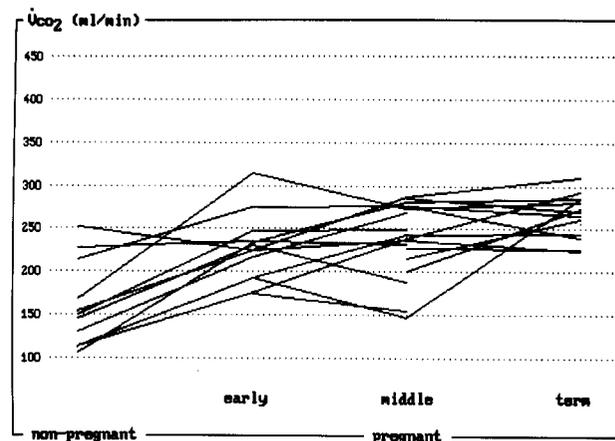
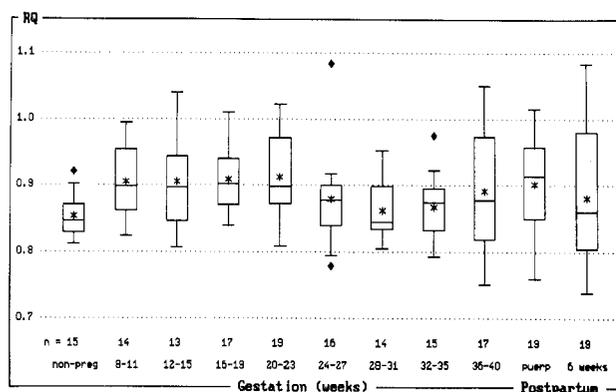
Fig. 3.8. Individual curves for carbon dioxide production (\dot{V}_{CO_2}).

Fig. 3.9. 'Box and whisker' plot of respiratory quotients (RQ).

could be due in part to weight differences, therefore Fig. 3.5 shows the values for $\dot{V}_{O_2}/\text{weight}$. The initial increase was again 40%, increasing from a median value of 3.0 to 4.2 ml/min/kg at 8-11 weeks gestation. Thereafter \dot{V}_{O_2}/kg remained more or less constant. A peak of 5.0 ml/min/kg was noted in the early puerperium. A fall had occurred by 6-8 weeks after delivery, although the value was still 13% higher than at 8-12 months after delivery (which we have taken as the non-pregnant level).

Oxygen consumption (\dot{V}_{O_2}) in individual pregnant women varied as much as $\dot{V}_{O_2}/\text{weight}$, but all the women showed an initial increase (Fig. 3.6). No typical pattern of individual changes was identified either in \dot{V}_{O_2} or in $\dot{V}_{O_2}/\text{weight}$.

Discussion

Widlund (1945), studying 60 non-pregnant and 157 pregnant women, found a gradual increase in \dot{V}_{O_2} from a mean of 210 ml/min in the non-pregnant women to 267 ml/min at term. Artal *et al.* (1986a) studied 88 pregnant women at 29±1.6 weeks gestation and found a mean value of 3.0 ml/min/kg compared with 2.5 in 39 non-pregnant women; our results represent an increase of 40% in \dot{V}_{O_2} . De Swiet (1980b) considered the most likely increase in oxygen consumption to be 40 ml/

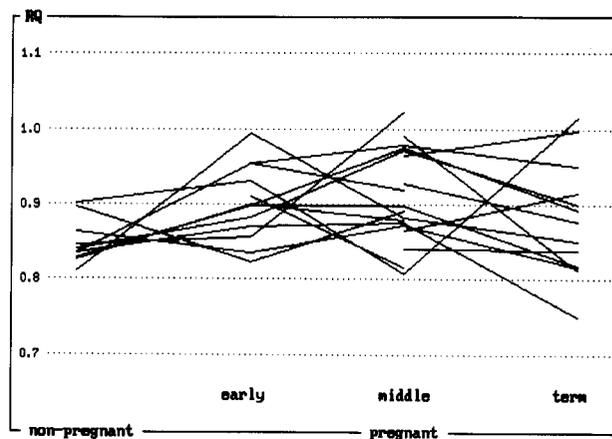


Fig. 3.10. Individual curves for respiratory quotients.

min. This agrees with a balance calculation that he made of the estimated extra demand for oxygen for the different body components changing during pregnancy. In a longitudinal study Pernoll *et al.* (1975) found a mean \dot{V}_{O_2} of 257 ml/min 6-12 months post partum compared with 331 ml/min at the end of pregnancy. Thus their levels were higher than ours, but their increase of 74 ml/min of the mean value should be compared to our median increase of 106 ml/min.

From the $\dot{V}_{O_2}/\text{weight}$ plot it appears that this variable remains stable during pregnancy, but if we take into account the fact that there is an increase in total body water of about 7 kg by the end of pregnancy and that less oxygen is required, at least for part of this, the picture changes somewhat. *Pari passu*, with the increase in water, $\dot{V}_{O_2}/\text{weight}$ would increase and at the end of pregnancy it would be 4.9 ml/min/kg instead of the median of 4.4 shown in Fig. 3.5 on the extreme assumption that the 7 kg of water needed no oxygen at all. The value of 4.2 ml/min/kg at 8-11 weeks gestation would be unaffected as the weight changes do not take place as early as this.

It is noteworthy that the inter-individual variability also remains conspicuous after standardization for weight. The differences in our results may be due to differences in position, room temperature, length of pre-test rest, technical differences, or points of reference. However, in a longitudinal study the

absolute level is less important than the relative changes. The technical aspects are further discussed in connection with the ventilatory equivalent, and the reference point is considered in the general discussion.

3.3 Carbon dioxide production

Figure 3.7 shows the course of the carbon dioxide production, which was similar to that of $\dot{V}O_2$. The same applied to the individual variations. (Fig. 3.8). Whatever difference there may have been between the $\dot{V}O_2$ and the $\dot{V}CO_2$ plots depended upon differences in RQ, which therefore might repay further investigation.

3.4 Respiratory quotient

The non-pregnant median value was 0.84 (Fig. 3.9). There was an increase early in pregnancy up to 0.91. From 24 weeks the median value began to fall to 0.85, only to increase again in the last months and during the puerperium when the value was again 0.91. This initial increase was not statistically significant.

The individual variations were marked. Seven women showed no clear change in RQ. The others showed the initial increase but there were some differences in when the peak values were attained (Fig. 3.10).

Discussion

Although the women were sitting and had had a meal before the study, and were therefore not in the optimum resting state

for monitoring basal metabolism, the term 'respiratory quotient' is used, as the values obtained at rest are close to the basal values and are the only data available that may indicate changes in the fuel metabolized during the course of pregnancy. As stated, the conditions were always the same throughout the whole longitudinal study.

The difficulties in assessing respiratory variables are usually reduced by repeated sequential measurements. As this cannot be done in pregnant women, particularly not when several variables are studied, it must be expected that the values will vary more than under other circumstances. This is also evident from the literature. It is particularly apparent when looking at RQ. The individual $\dot{V}CO_2$ and $\dot{V}O_2$ values may not indicate any large error, but RQ will amplify them. The standard values for RQ in a subject on a normal mixed diet is 0.83, that is, virtually the same as in the present study, but few if any of the studies in pregnant or non-pregnant women give this value. Since RQ values greater than 1 are theoretically impossible, it will be seen that some of the values must be viewed with caution. The box plots include values greater than 1 mainly because the 25–75th centiles box is so broad. Only a few of the included values are between 1 and 1.05. Whether they reflect leaking masks, temporary hyperventilation or true metabolic changes is difficult to know.

An increase in RQ during pregnancy was noted by some earlier observers, including Knuttgen & Emerson (1974) who found a non-pregnant mean RQ of 0.76 compared with 0.83 in the pregnant women. This increase in RQ of 0.07 is the same as shown in Fig. 3.9 and, if true, can only be interpreted as increased glucose utilization. Pernoll *et al.* (1975) also found no significant differences between the pregnant and the non-pregnant women.

4. Ventilation

4.1 Ventilation per min

As shown in Fig. 4.1, an immediate 12% increase in \dot{V} had occurred by 8–11 weeks gestation. Thereafter there was a further gradual increase in \dot{V} until term, which was statistically significant by 20–23 weeks gestation. The minute volume decreased again after delivery. Overall the median level changed from 9.4 l/min in the non-pregnant woman to 12.6 l/min at 40 weeks gestation.

The individual changes were most varied and followed no clear pattern except that the initial increase was noted in 15 women and there was a general trend to higher values late in pregnancy. In four women the initial increase was lacking, and three of them retained virtually the same \dot{V} during the whole study period (Fig. 4.2).

4.2 Respiratory rate

Figure 4.3 shows that median respiratory rate remained between 16 and 18 breaths/min at rest in the non-pregnant as well as in the pregnant women. By 20–27 weeks gestation the median values were significantly lower than in the non-pregnant state. The lines tended to be parallel, that is, those women who had a low, median or high respiratory rate when non-pregnant tended to maintain this when pregnant (Fig. 4.4).

4.3 Tidal volume

As the increase in the median \dot{V} during pregnancy was not due to an increase in respiratory rate, there must have been an increase in tidal volume. This is seen in Fig. 4.5.

There was a significant increase in median V_T from 560 ml in the non-pregnant women to 630 ml in early pregnancy, an increase of some 15%. This was followed by a further augmentation until term when the V_T was 715 ml (27% higher than the non-pregnant value). The return to a lower level began in the puerperium and was attained by 6–8 weeks after delivery.

As shown in Fig. 4.5, the results varied widely. This was all the more evident when the individual changes were studied. Ten women showed the same pattern as seen in Fig. 4.6. In three women there was only an initial increase, and in one the tidal volume did not change systematically. In the rest there was an increase that began or ended at various times during pregnancy.

Discussion

As $\dot{V}O_2$ and $\dot{V}CO_2$ increase, and have to increase, during pregnancy, ventilation must also increase and/or improve. We found a 35% increase in median \dot{V} compared with 40% reported in the review by De Swiet (1980b), who noted an overall average increase from 7.5 l/min in the non-pregnant state to 10.5 l/min in late pregnancy. Thus our level of \dot{V} seems

to be higher than those reported in most earlier studies. Many of the earlier research workers only had spirometers with a rather high resistance, which tended to give lower values for \dot{V} .

Most authors agree that during pregnancy f_R remains more or less constant at rest, thus the increase in \dot{V} must be due mainly to increased V_T . In his review Bonica (1974) noted a 15% increase in respiratory rate. Looking at both mean and median values we did note a small decrease in median f_R compared with non-pregnant levels. This lasted until 32 weeks gestation. If anything, these results confirm that V_T must be the main cause of the increased \dot{V} . All previous studies agree that there is an increase in \dot{V} , and values between 25% and 35% have been reported, although Artal *et al.* (1986a) in their large series give a value of 38%. We found a 27% increase in median V_T by 36–40 weeks gestation compared with non-pregnant levels.

4.4 Alveolar ventilation

The most interesting ventilatory variable is the alveolar ventilation as this reveals the ventilation at the point of gas exchange.

As shown in Fig. 4.7, alveolar ventilation was significantly increased to 6.2 l/min (an 80% increase) by 8–11 weeks gestation. At term the level was 6.5 l/min. In the puerperium alveolar ventilation began to decrease. Six weeks after delivery the median value was 4.5 l/min compared with 3.4 l/min at 12 months after delivery.

The individual variations in alveolar ventilation were less pronounced than in the other respiratory variables discussed so far. The initial increase was present in all women. In nine of them the patterns resembled that seen in Fig. 4.8, whereas in the others the peak values occurred at different times during pregnancy.

Discussion

Bonica (1974) in his review stated that alveolar ventilation was about 70% above normal at term and 'until recently, the increase was thought to be progressive throughout pregnancy, but recent data show that almost maximal hyperventilation occurs as early as the second or third months of gestation'. Pernoll *et al.* (1975) studied 12 women at 30 weeks gestation and found that alveolar ventilation was 50% higher than the non-pregnant level obtained 12–14 weeks post partum. It is of interest to note that in the present study levels at 6 weeks after delivery were still higher than those obtained at 12 months after delivery. This was true for most of the variables studied and is further referred to in the general discussion.

4.5 Ventilation equivalent for oxygen

Ventilation equivalent for oxygen is the volume of air in litres

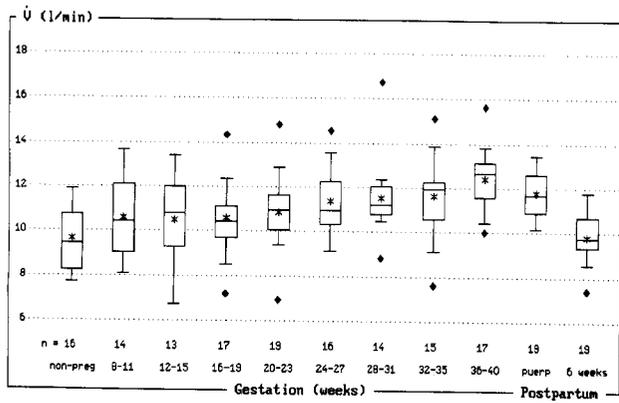


Fig. 4.1. 'Box and whisker' plot of ventilation minute volume (\dot{V}).

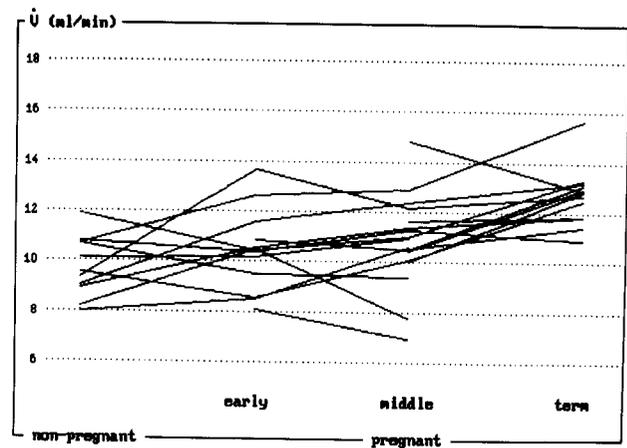


Fig. 4.2. Individual curves for ventilation minute volume.

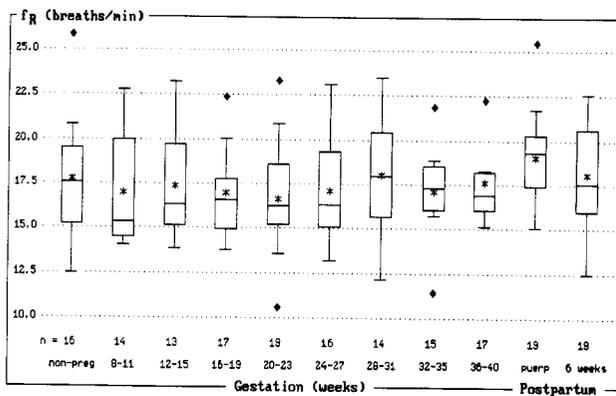


Fig. 4.3. 'Box and whisker' plot of respiratory rate (f_R).

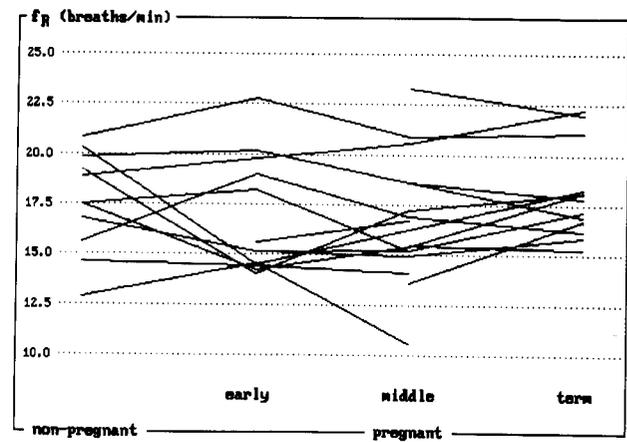


Fig. 4.4. Individual curves for respiratory rates.

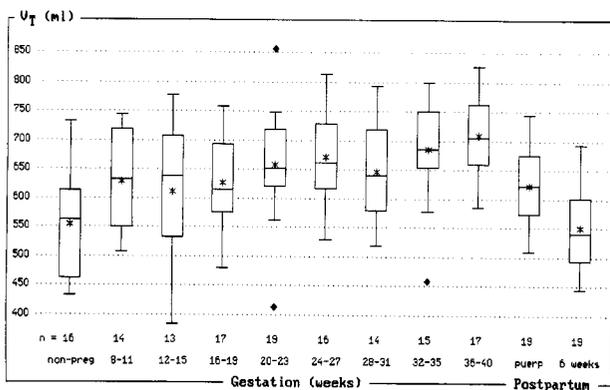


Fig. 4.5. 'Box and whisker' plot of tidal volume (V_T).

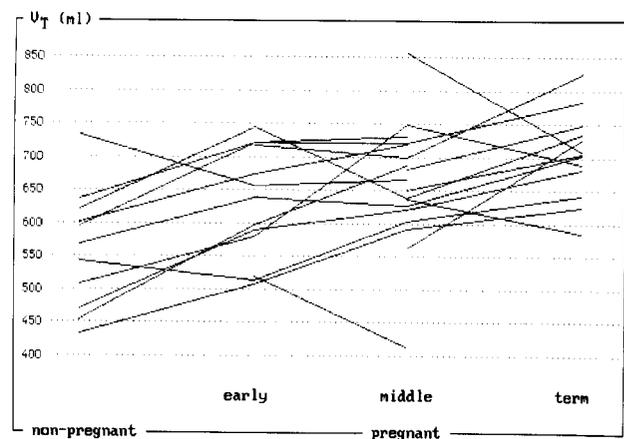


Fig. 4.6. Individual curves for tidal volume.

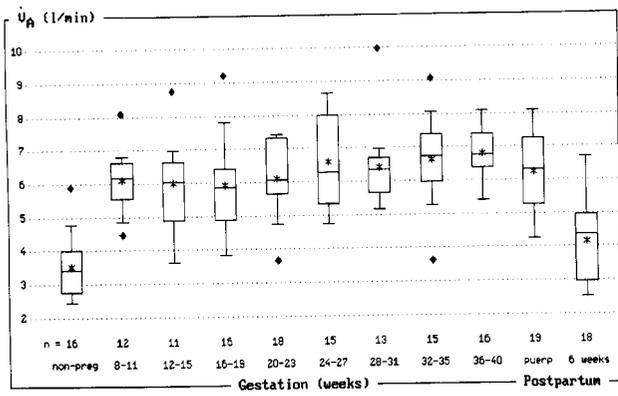


Fig. 4.7. 'Box and whisker' plot of alveolar ventilation (\dot{V}_A).

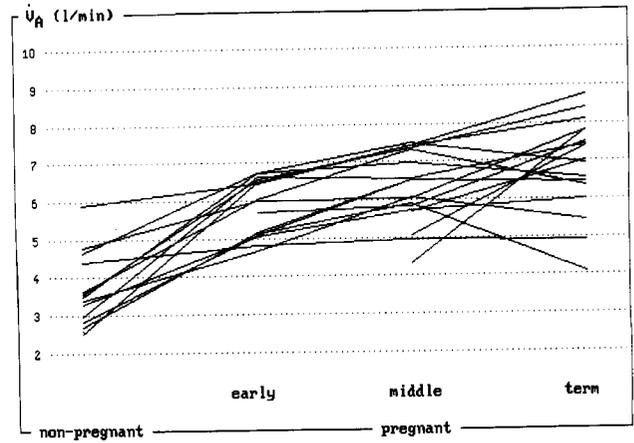


Fig. 4.8. Individual curves for alveolar ventilation.

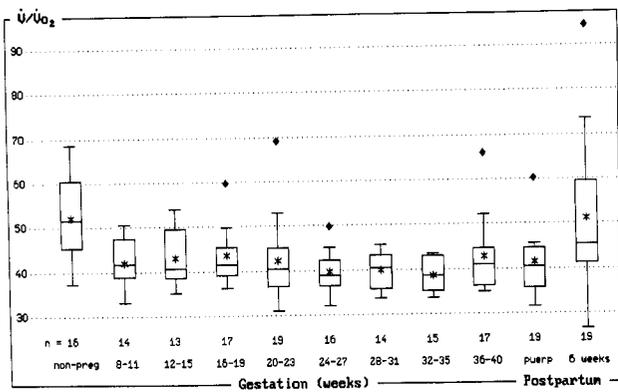


Fig. 4.9. 'Box and whisker' plot of ventilatory equivalent for oxygen (\dot{V}/\dot{V}_{O_2}).

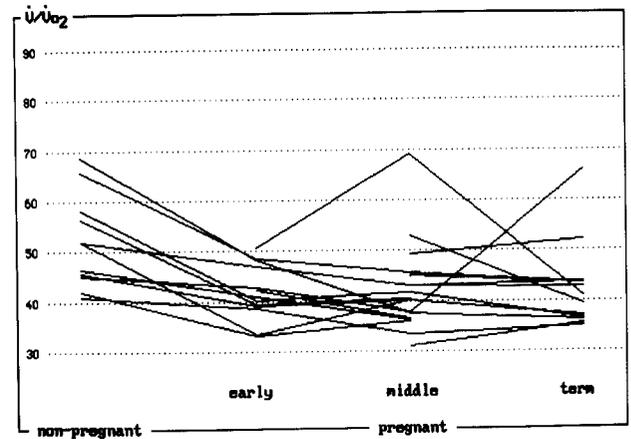


Fig. 4.10. Individual curves for ventilatory equivalent for oxygen.

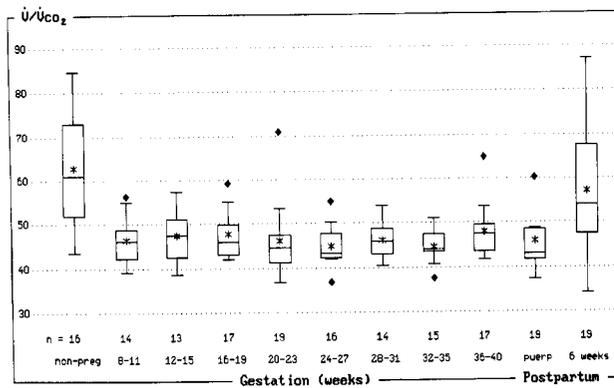


Fig. 4.11. 'Box and whisker' plot of ventilatory equivalent for carbon dioxide (\dot{V}/\dot{V}_{CO_2}).

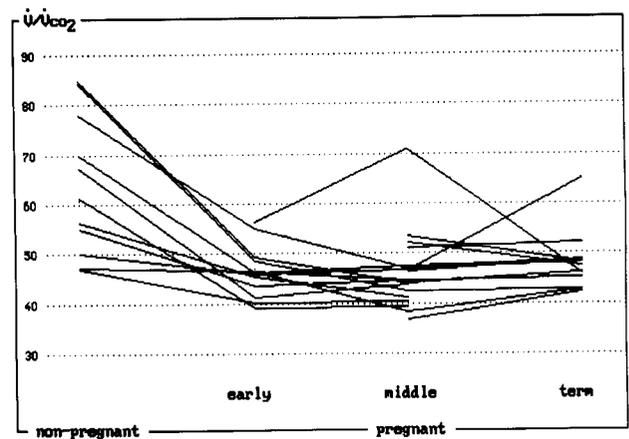


Fig. 4.12. Individual curves for ventilatory equivalent for carbon dioxide.

that must be inhaled for the absorption of 1 litre of oxygen (Fig. 4.9). The non-pregnant women had median values of about 50. Already by 8–11 weeks gestation the ventilation equivalent for oxygen fell significantly to about 40 and remained more or less stable during the pregnancy and puerperium. Six weeks post partum \dot{V}/\dot{V}_{O_2} had risen to 44.

There was the usual tendency for the lines to be parallel but the individual variations were small as seen from Fig. 4.10. In two women, \dot{V}/\dot{V}_{O_2} was only marginally lower during pregnancy and the puerperium than in the control period.

4.6 Ventilation equivalent for carbon dioxide

Figure 4.11 illustrates the initial fall from the non-pregnant level of 60 down to 45, and a pattern which resembles that of \dot{V}/\dot{V}_{O_2} except that the reduction in \dot{V}/\dot{V}_{CO_2} was about 28% compared with 22% for \dot{V}/\dot{V}_{O_2} . This reduction was also statistically significant. The individual curves of \dot{V}/\dot{V}_{CO_2} are also similar to those of \dot{V}/\dot{V}_{O_2} (Fig. 4.12).

Discussion

If RQ had remained constant during pregnancy, the relative decrease in the ventilation equivalents would have been equal as $\dot{V}/\dot{V}_{O_2} : \dot{V}/\dot{V}_{CO_2} = RQ$. However, as RQ increased from the non-pregnant median of 0.84 to 0.90, \dot{V}/\dot{V}_{CO_2} fell correspondingly more than \dot{V}/\dot{V}_{O_2} .

Pernoll *et al.* (1975) described values for \dot{V}/\dot{V}_{O_2} of about 35 in both non-pregnant and pregnant women studied at monthly intervals, which is in keeping with the fact that they saw no changes in RQ, but still surprising in view of the increase they observed in alveolar ventilation. Artal *et al.* (1986b) found a decrease in \dot{V}/\dot{V}_{O_2} from 42 to 35 in a comparison of non-pregnant with pregnant levels. Thus they described the same direction of changes as we have found, but our levels were higher.

De Swiet (1980b) stated that 'with oxygen consumption increasing by less than 20% and minute ventilation increasing by more than 40% it is clear that there is considerable hyper-

ventilation, and ventilatory equivalent is therefore considerably raised in pregnancy. To take average figures it rises from about 3.2 litres per 100 ml to almost 4.0 litres per 100 ml of oxygen consumed.' We found a 40% increase in median \dot{V}_{O_2} as early as 8–11 weeks gestation (Fig. 3.3) and the increase in \dot{V} was then only 12% (Fig. 4.1).

These contradictory results merit some comment. Our values for both \dot{V}_{O_2} and \dot{V}_{CO_2} are within the range of most published studies, whereas \dot{V} at 9.4 litres is higher than the value of about 7.0 litres reported by most other authors. By dividing \dot{V} by \dot{V}_{O_2} some of the studies found a fall in \dot{V}/\dot{V}_{O_2} during pregnancy, and some found an increase. This illustrates that rather small differences due to variations in the individual subjects, and/or the measuring arrangements, may lead to different results. It also demonstrates how careful we must be not to generalize too much from the results from one study in spite of the fact that, as in the present one, \dot{V}/\dot{V}_{O_2} decreased in each of the 20 women studied and markedly in 18.

\dot{V}_{O_2} is obtained from the primary measurements of \dot{V} and the fraction of expired oxygen (Fe_{O_2}) concentration as described by Bartels *et al.* (1959). $\dot{V}_{O_2} = \dot{V} \times (Fi_{O_2} - Fe_{O_2})$ and Fi_{O_2} is a constant. If we divide the ventilatory equivalent for oxygen by \dot{V} we have $1/(Fi_{O_2} - Fe_{O_2})$. Thus, the ventilatory equivalent for oxygen depends on monitoring the oxygen concentration during expiration. In our non-pregnant women, we found a median \dot{V}/\dot{V}_{O_2} of 52, when \dot{V} was 9.4. Using instead the most commonly reported value of 7.0, the ventilatory equivalent for oxygen would have been 37. In no other presentation is the 'pure oxygen measurement' revealed. The alveolar or end-expiratory CO_2 and mixed venous CO_2 as well as cardiac output are dominated by the CO_2 levels. As discussed below, our CO_2 levels are relatively low. This is also true for the oxygen levels. The fact that the \dot{V}_{O_2} and \dot{V}_{CO_2} levels are similar to those of most other studies is due to the multiplication of high \dot{V} and low gas levels. As our calibrations were routinely and carefully performed twice a day, we do not think that our findings are mistaken; we can only state that they differ from those of others, and from which primary measurements the differences stem.

5. Alveolar carbon dioxide

5.1 Alveolar P_{CO_2}

Figure 5.1 demonstrates that alveolar P_{CO_2} (that is, the end-expiratory P_{CO_2}) decreased in early pregnancy. There was a statistically significant drop in median P_{ACO_2} of about 0.53 kPa (4 mmHg). The median values oscillated within 0.13 kPa (1 mmHg) during pregnancy and increased towards the non-pregnant level in the early puerperium.

The inter-individual variations were smaller than in any other variable (Fig. 5.2).

Discussion

In subjects with healthy lungs, alveolar P_{CO_2} is virtually equal to arterial P_{CO_2} . The lower P_{CO_2} during pregnancy was first described independently by Hasselbalch & Lundsgaard (1912) and Leimdörfer *et al.* (1912), and their results have been confirmed in many subsequent studies that monitored P_{ACO_2} , P_{aCO_2} or arterialized capillary blood. Siggaard-Andersen

(1963) gave the normal P_{aCO_2} for women as 5.1 kPa (38 mmHg). Such high mean or median levels were not seen in our study. Six weeks after delivery, the median values were still lower than those obtained 8-12 months after delivery.

In their review of maternal and fetal blood gases and acid-base balance, Huch & Huch (1984) quoted mean arterial P_{CO_2} values for pregnant women of between 3.5 kPa and 4.5 kPa (26.4 mmHg and 33.6 mmHg). Most of them were about 4.3 kPa (32 mmHg).

The fall in median P_{ACO_2} during pregnancy of 0.53 kPa (4 mmHg) is less than the mean 0.8 kPa (6 mmHg) in the series reported by Bouterline-Young & Bouterline-Young (1956) or 0.93 kPa (7 mmHg) reported by Lyons & Antonio (1959). The pregnant level is very close to that of the above authors.

5.2 P_{CO_2} of the mixed venous blood

It is obvious that when median arterial P_{CO_2} decreases during pregnancy, median P_{VCO_2} will also decrease. This is confirmed

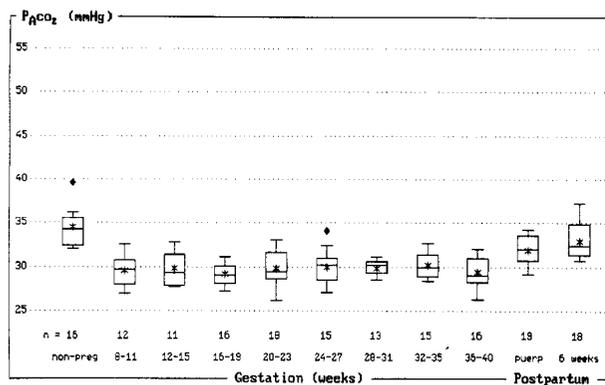


Fig. 5.1. 'Box and whisker' plot of alveolar P_{CO_2} .

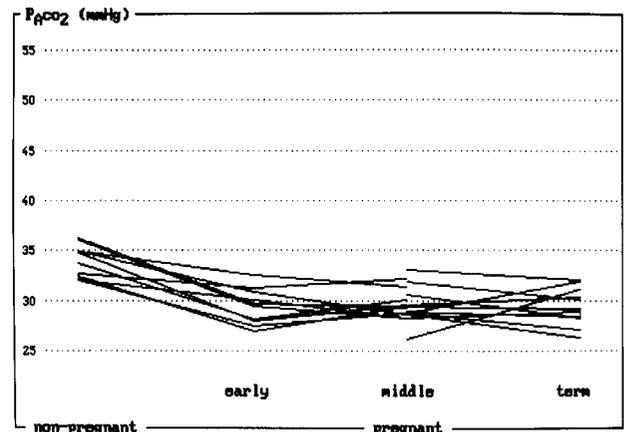


Fig. 5.2. Individual curves for alveolar P_{CO_2} .

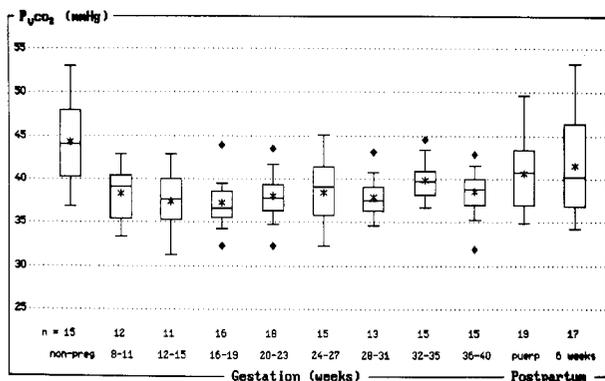


Fig. 5.3. 'Box and whisker' plot of mixed venous P_{CO_2} .

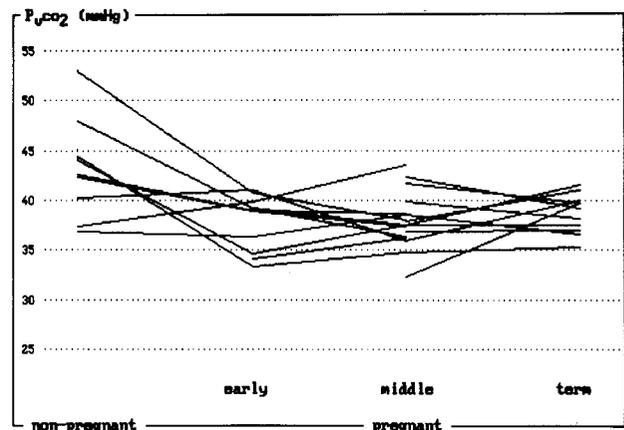


Fig. 5.4. Individual curves for mixed venous P_{CO_2} .

in Fig. 5.3. The median non-pregnant value was 5.9 kPa (44 mmHg), and during pregnancy it was about 5.1 kPa (38 mmHg). This fall was statistically significant by 8–11 weeks gestation.

There were some individual variations (Fig. 5.4). In three women hardly any changes were noted during pregnancy, and in three women $\bar{P}\bar{v}co_2$ remained low during the puerperium.

Discussion

The rebreathing technique (Campbell & Howell 1962) used in

this study gives a mixed venous Pco_2 that agrees with the Pco_2 found in the pulmonary artery. Mixed venous Pco_2 has not been studied previously in pregnancy, probably because such data would not add to the information derived from measurements of $PAco_2$ or $Paco_2$. $\bar{P}\bar{v}co_2$ is included here as this value is needed for the calculation of cardiac output using the indirect Fick equation. Our non-pregnant median level is 0.26 kPa (2 mmHg) lower than the normal values given by Comroe *et al.* (1962) and Ganong (1979), and 0.8 kPa (6 mmHg) lower than those reported by Campbell & Howell (1962) and Denison *et al.* (1971).

6. Transcutaneous P_{CO_2} and P_{O_2}

6.1 tcP_{CO_2}

A further estimation of arterial P_{CO_2} was obtained using the transcutaneous technique. The results are shown in Fig. 6.1. The distinct fall during pregnancy was noted later than in PA_{CO_2} (Fig. 5.1), decreasing from a median non-pregnant level of 8.8 kPa (66 mmHg) to about 6.9 kPa (52 mmHg) during pregnancy, a decrease of 20% which was statistically significant at 20-23 weeks gestation.

In general, the individual curves (Fig. 6.2) were stratified with the same direction of changes as seen in Fig. 6.1.

Discussion

The level of tcP_{CO_2} is of course different from PA_{CO_2} values as uncorrected tcP_{CO_2} values are given. The increased temperature elevates P_{CO_2} and, furthermore, CO_2 is added by skin metabolism. The latter corresponds to about 0.53 kPa (4 mmHg) according to Severinghaus (1966). He also gives a factor of 1.4 for the relation between PA_{CO_2} and tcP_{CO_2} due to the

temperature difference between the blood and the electrode. This factor is not infrequently part of the software of the tcP_{CO_2} equipment. This factor varies, and Rooth *et al.* (1987) used a value of 1.6 for adult men. Using the 1.6 value, the non-pregnant level would be 5.2 kPa (39 mmHg) and the pregnant level 3.9 kPa (29 mmHg). Thus the pregnant level of tcP_{CO_2} would correspond to that of PA_{CO_2} , whereas the latter was lower than expected in the non-pregnant state.

Using the factor 1.4 our pregnant level would be 4.4 kPa (33 mmHg), and this agrees with that of the authors cited earlier, but the non-pregnant level would be 5.9 kPa (44 mmHg).

6.2 tcP_{O_2}

The tcP_{O_2} results are shown in Fig. 6.3. There was a distinct increase during pregnancy, with a median value of oscillation around 10.7 kPa (80 mmHg) compared with 10.0 kPa (75 mmHg) in the non-pregnant women. This was statistically significant at 8-11 weeks gestation. As was found for P_{CO_2} , the

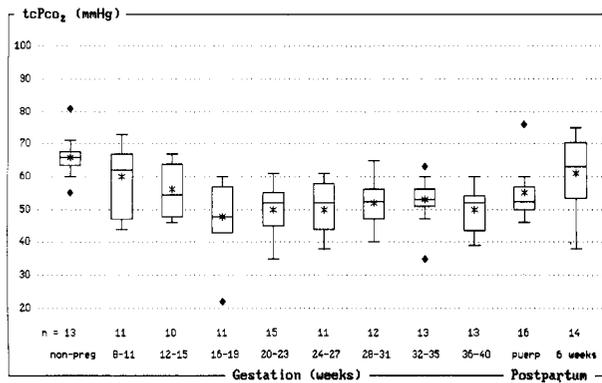


Fig. 6.1. 'Box and whisker' plot of transcutaneous P_{CO_2} .

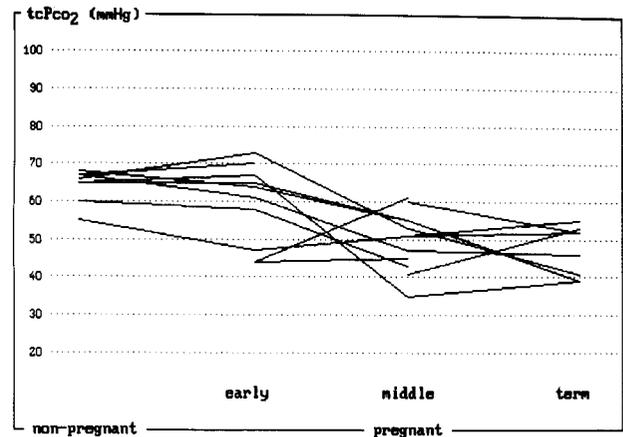


Fig. 6.2. Individual curves for transcutaneous P_{CO_2} .

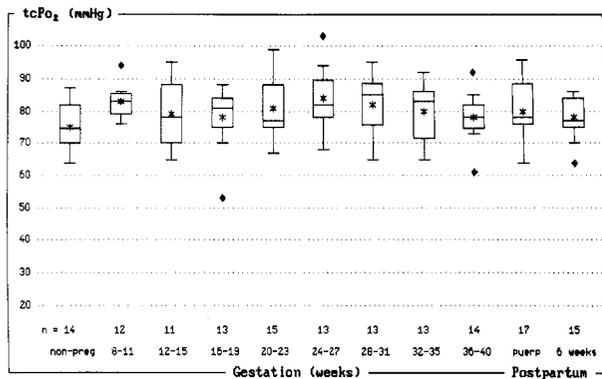


Fig. 6.3. 'Box and whisker' plot of transcutaneous P_{O_2} .

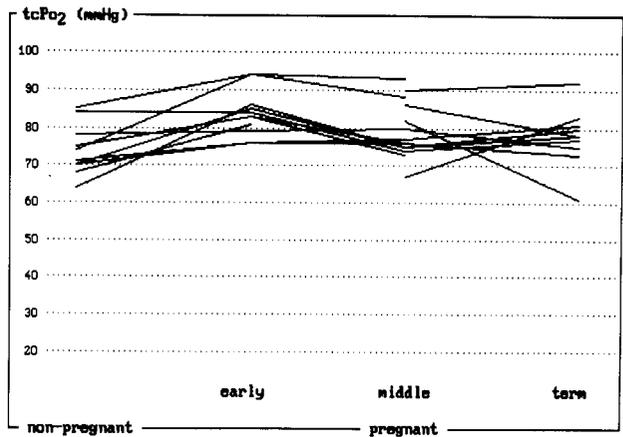


Fig. 6.4. Individual curves for transcutaneous P_{O_2} .

dominant pattern for the individual curves (Fig. 6.4) was one of stratification.

Discussion

Only a few studies have compared arterial Po₂ between pregnant and non-pregnant women (Huch & Huch 1984). Stojanov (1972) reported a mean value of 11.5 kPa (86.3 mmHg) in non-pregnant women compared with 12.5 kPa (93.9 mmHg) in pregnant women (an increase of 9%), and Kusche *et al.* (1986) found a mean arterial Po₂ of 11.5 kPa (86 mmHg) at 5–10 weeks after delivery compared with 13.3 kPa (100 mmHg) in

early pregnancy (an increase of 16%) and 12.5 kPa (94 mmHg) at 16–20 weeks gestation (a 9% increase).

The change in PAo₂ due to the decreased PAco₂ may be calculated from the alveolar gas equation assuming that the diffusion capacity is unchanged. When PAco₂ decreases from 4.5 to 3.9 kPa (34 to 29 mmHg) and RQ changes from 0.84 to 0.91, PAo₂ would increase from 14.3 to 15.3 kPa (107 to 115 mmHg), an increase of 7%. Thus, the percentage increase in the calculated PAo₂ induced by hyperventilation is the same as that for tcPo₂. It has been known since the earliest studies of tcPo₂ that the adult absolute values tend to be 10–20% lower than arterial Po₂ (Huch *et al.* 1981).

7. Circulation

7.1 Heart rate

As shown in Fig. 7.1, heart rate was usually higher during pregnancy, with peak values between 28 weeks and term. The median non-pregnant level was 80 b.p.m. and the peak was 94 b.p.m. at 28–31 weeks gestation (an increase of 18%). The median increase was statistically significant from 20–23 weeks gestation compared with the non-pregnant level. In the puerperium, heart rate dropped to below the non-pregnant value. The largest drop seen was 32 b.p.m. The intra-individual variations were marked, and it is difficult to find any clear patterns (Fig. 7.2). In seven women there were no major differences in heart rate between the pregnant and non-pregnant state.

Discussion

Hyttén & Leitch (1971) stated that the evidence that heart rate increased during pregnancy was almost unanimous, and they quoted a mean increase in heart rate of 15/min, similar to that seen in our study.

7.2 Cardiac output

Figure 7.3 shows the cardiac output at different times during pregnancy. There was a statistically significant increase from the resting median level of 2.6 l/min to 3.8 by 8–11 weeks, and a further but slower increase during 12–15 weeks gestation with a peak value of 4.7 l/min. Thereafter, the level fluctuated between 4.3 and 4.6 l/min for the remainder of the pregnancy and the puerperium. Six weeks post partum \dot{Q} was down to 3.4 l/min, that was about halfway between the pregnant and the non-pregnant level. Figure 7.4 shows that, with one exception, \dot{Q} increased when the women became pregnant. From mid-pregnancy to term \dot{Q} increased in some, remained constant in others, and decreased in five women.

7.3 Cardiac output per unit of weight

As cardiac output is often expressed as \dot{Q}/weight , this is

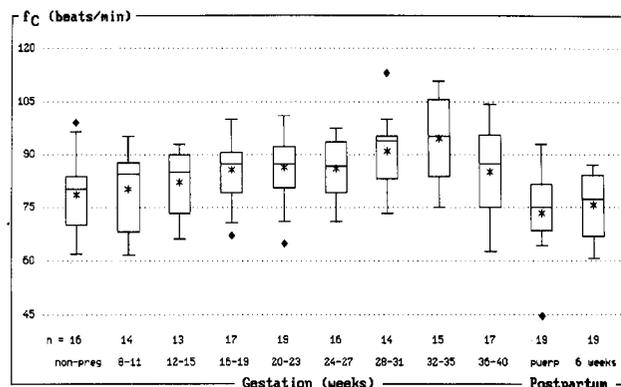


Fig. 7.1. 'Box and whisker' plot of heart rate (f_c).

depicted in Fig. 7.5. As can be expected when the increase in weight is taken into account, the decrease was more marked than that shown Fig. 7.3. The peak value was between 12 and 15 weeks gestation. The increase from the non-pregnant level of 0.04 l/min to 0.06 l/min by 8–11 weeks gestation was statistically significant. The decline was gradual until term. In the puerperium there was a shift to a higher level (Fig. 7.6).

Although there were some exceptions, the individual curves showed an increase in \dot{Q}/weight when the women became pregnant, and a fall towards term (Fig. 7.6).

7.4 Stroke volume

Cardiac output per heart beat, that is, stroke volume, is displayed in Fig. 7.7. From a non-pregnant level of 30 ml, stroke volume increased during pregnancy to 50 ml by 8–11 weeks ($P=0.021$). Except for an occasionally higher median value at 12–15 weeks gestation, the level remained the same during pregnancy. In the puerperium the median stroke volume was above 60 ml, twice the non-pregnant level. Six weeks after delivery median stroke volume was 46 ml, halfway down to the non-pregnant level.

The individual curves for stroke volume showed much variability and crossing of the lines, but stroke volume was consistently higher in the pregnant than in the non-pregnant state (Fig. 7.8).

Discussion

In both the non-pregnant and pregnant women our values for \dot{Q} were lower than those reported previously. Although our values for weight and heart rate were similar to reported values, our values for \dot{Q}/weight and stroke volume were lower than those of other studies. Hamilton (1949) reported a value of 4.5 l/min and Ueland *et al.* (1969) a value of 5.0 l/min in the non-pregnant woman, rising to 7.0 l/min at 28–32 weeks gestation. The latter study used the dye dilution method, which is probably the most reliable. The indirect Fick method used in our study was chosen

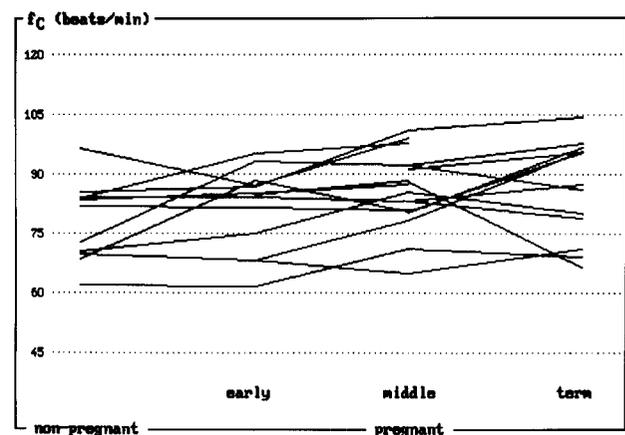


Fig. 7.2. Individual curves for heart rate.

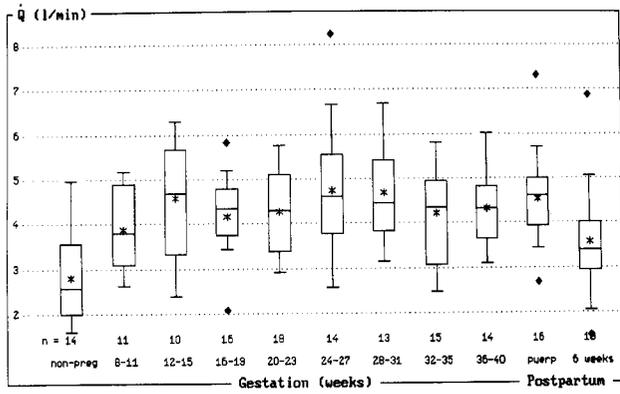


Fig. 7.3. 'Box and whisker' plot of cardiac output (\dot{Q}).

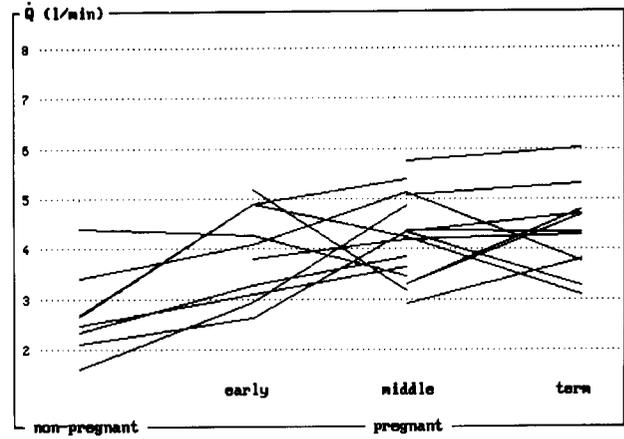


Fig. 7.4. Individual curves for cardiac output.

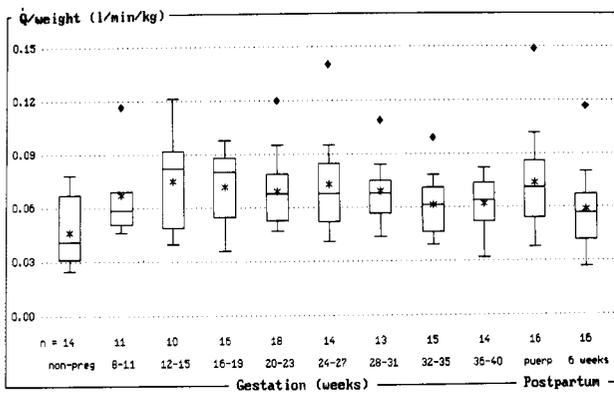


Fig. 7.5. 'Box and whisker' plot of cardiac output per kg of weight.

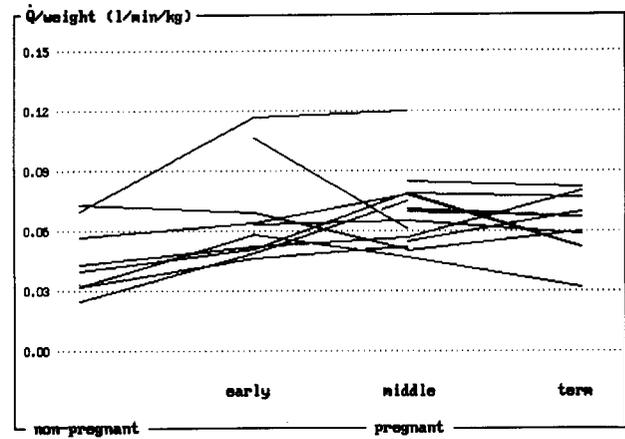


Fig. 7.6. Individual curves for cardiac output per kg of weight.

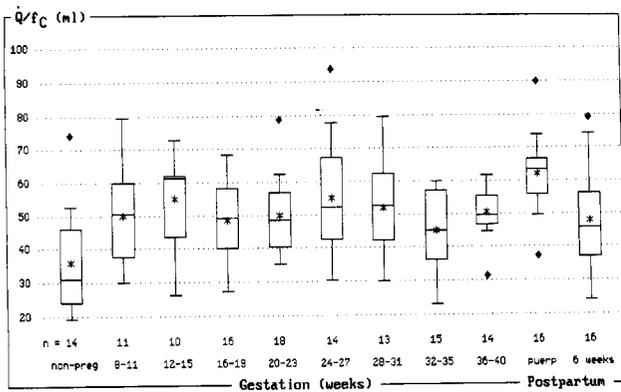


Fig. 7.7. 'Box and whisker' plot of stroke volume (\dot{Q}/f_c).

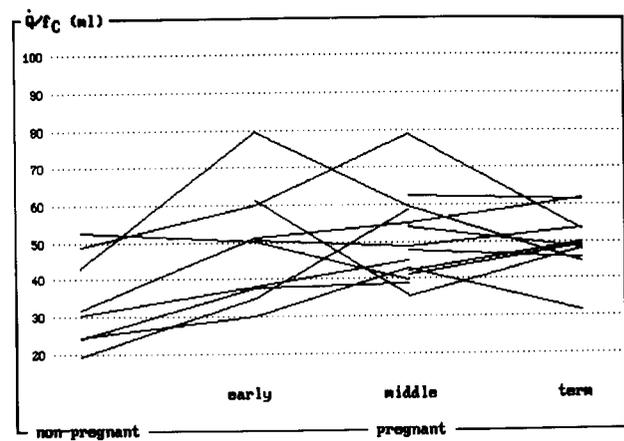


Fig. 7.8. Individual curves for stroke volume.

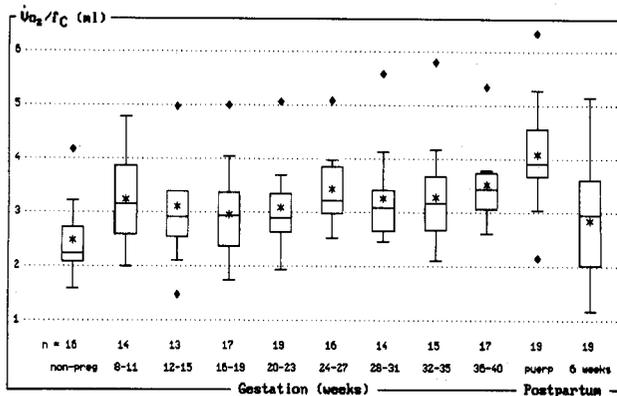


Fig. 7.9. 'Box and whisker' plot of oxygen pulse ($\dot{V}O_2/f_C$).

because it only entails one additional and still non-invasive measurement, i.e. that of $PvCO_2$. Denison *et al.* (1971) found this to be an excellent method, but Reybrouck *et al.* (1978) considered it unreliable.

There are several possible explanations for our low \dot{Q} value. As discussed in connection with the ventilatory equivalents, our values for \dot{V} tended to be higher, and those for O_2 and CO_2 lower than those usually quoted. The formula used for calculating the cardiac output ($\dot{V}CO_2/c\bar{v}CO_2 - cACO_2$) shows how dependent the calculated \dot{Q} is upon the CO_2 measurements.

As discussed in Chapter 5.2, our $PvCO_2$ level was between 0.26 and 0.8 kPa (2 and 6 mmHg) lower than in the literature cited. As \dot{Q} is obtained from $\dot{V}CO_2/c\bar{v}CO_2 - cACO_2$, \dot{Q} may become too low if $\dot{V}CO_2$ or $cACO_2$ are low or $c\bar{v}CO_2$ is high. $c\bar{v}CO_2$ was calculated from $P\bar{v}CO_2$ and a standard dissociation curve. We have no means of knowing if the dissociation curve used is more valid in the non-pregnant than in the pregnant state. \dot{Q} was low both during and particularly after pregnancy. As discussed, all Pco_2 values were low, partly because of hyperventilation and possibly also due to some systematic sampling error of the exhaled air. The level of \dot{Q} was low, but as \dot{Q} changed with pregnancy parallel to the finding of other studies, we assume that the patterns of change are correct. In the present study we have been more concerned with the changes seen between the non-pregnant and the pregnant state as well as the individual variations. Such information is revealed in spite of the differences in the absolute values.

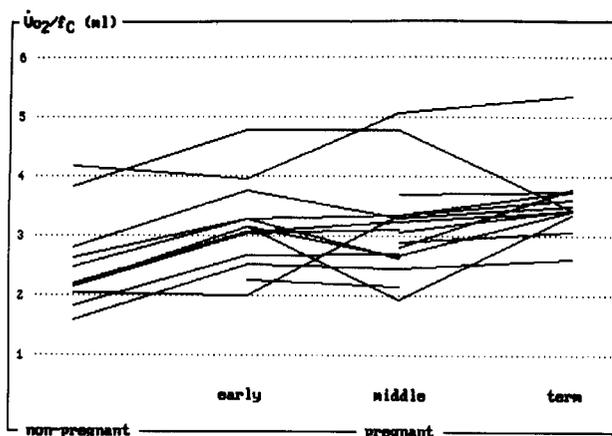


Fig. 7.10. Individual curves for oxygen pulse.

A great number of published studies of \dot{Q} in pregnant and non-pregnant women have used various techniques (see Nisell *et al.* 1985). Most of them have studied the pregnant women in the supine position. With the progression of pregnancy, the uterus compresses the venous return more and more, which partly accounts for the drop in \dot{Q} in late pregnancy noted in the earlier studies, and it is possible that venous return is also reduced in the sitting position (Schneider *et al.* 1984; Huch *et al.* 1986). Ueland *et al.* (1969) found a mean \dot{Q} of 6.9 l/min in sitting pregnant women at 22 weeks gestation. At term mean \dot{Q} was 5.7 l/min. Thus the direction of the changes is similar in our studies. Other investigations, such as those described by Atkins *et al.* (1981) or McLennan *et al.* (1987) using a Doppler ultrasound technique are difficult to assess due to pregnancy-related changes in the conditions for the calculations (Robson *et al.* 1987). However, regardless of the technique, they all found a reduction in cardiac output towards term.

7.5 Oxygen pulse

An indication of how the heart adapts to the increased oxygen demand is given by $\dot{V}O_2/f_C$, namely, the amount of oxygen transported by each heart beat. It will be seen from Fig. 7.9 that the median value increased from a non-pregnant level of 2.2 ml to 3.1 ml by 8–11 weeks gestation. This increase was statistically significant. After that, values remained basically unchanged throughout pregnancy. A peak of 3.8 ml was reached in the puerperium.

The individual variations were marked (Fig. 7.10). Two women showed no changes, whereas ten women had higher levels during pregnancy which peaked during the last month of gestation; six women only showed higher values during pregnancy.

Discussion

Astrand (1952) was the first to use the term 'oxygen pulse', considering it a useful measure to monitor the capacity of the cardio-pulmonary system. Obviously the higher the value, the more oxygen the heart can deliver without using up the latent reserve present in an increase in heart rate. Oxygen pulse is therefore used in sports medicine, but it does not seem to have been calculated in pregnancy.

With a 60% increase in stroke volume, it is obvious that the heart can deliver more oxygen per beat during pregnancy than before. $\dot{V}O_2/f_C$ was neither influenced by the 5% lower haemoglobin concentration at 24 weeks gestation nor by the normalization of oxygen capacity of the blood later in pregnancy. We found no covariation between these two variables.

There was already a distinct increase in $\dot{V}O_2$ by 8–11 weeks gestation, and the curve was similar to that in Fig. 7.1 showing heart rate. The net result was an increase in the median amount of oxygen transported per heart beat of about 45%, which remained essentially unchanged during pregnancy.

As median oxygen consumption was as high in the puerperium as during the pregnancy, but maternal heart rate fell by 17%, oxygen pulse reached its peak in the puerperium. The maternal heart is able, thanks to the previous adjustment in $\dot{V}O_2/f_C$, to supply the tissues with enough oxygen at a relatively low heart rate in spite of the fact that oxygen demand per unit weight in the puerperium remains as high as before.

8. Testing for initial anxiety and statistical summary

Most of the variables studied showed marked changes by 8–11 weeks gestation compared with non-pregnant levels. Anxiety, when the women were exposed to the tests for the first time, could be one of the explanations for this. Were this so, it would be expected that the second measurements would be more 'normal' than the first ones. The women were studied every second week, whereas the results are plotted per month as the same exercise tests were performed once a month. Table 2 gives the mean values of the main primary measurements at the first and at the second study period. It will be seen that there were no significant differences between the first and second measurements. As the primary values did not differ significantly, neither did the other values derived from them. Thus, whatever anxiety effect there may have been, it was not enough to be of statistical significance and would not have affected our findings indicating that there were already marked changes in the cardiopulmonary variables by 8–11 weeks gestation.

To take $\dot{V}O_2$ as an example, there were as many values higher at the first measurement as there were higher at the second measurement. Hypothetically it might be argued that those women who had higher values at the first measurement were apprehensive and in the other women the effect of pregnancy changes were demonstrated. It is more likely that the differences lie within the variability of the results. Similar, but again

Table 2. Testing for initial anxiety

Variable	Mean first measurement	Mean second measurement	Wilcoxon test <i>P</i>
$\dot{V}O_2$	242	254	1.00
$\dot{V}CO_2$	205	230	0.17
<i>V</i>	10.3	10.7	0.64
f_R	17.5	17.1	0.49
f_C	80.7	80.9	0.60
$PAco_2$	23.3	25.0	0.66
$P\bar{V}CO_2$	26.0	32.0	0.18

For abbreviations see Abbreviations section on p. iv.

not significant, differences were observed around 24 weeks gestation.

Table 3 summarizes the trends of the various physiological changes when the women became pregnant, giving the statistical significance and the weeks of gestation at which this first became apparent.

Table 3. Trends of change at rest during the pregnancy*

Variable	Trend*	<i>P</i> (Wilcoxon)	Gestation (weeks)
Weight	+	0.021	20–23
$\dot{V}O_2$	+	0.004	8–11
$\dot{V}CO_2$	+	0.006	8–11
$\dot{V}O_2/f_C$	+	0.008	8–11
$\dot{V}O_2/\text{weight}$	+	0.006	8–11
$\dot{V}CO_2/\text{weight}$	+	0.006	8–11
RQ	+	0.059	8–11
\dot{V}	+	0.007	20–23
f_R	–	0.017	20–23
\dot{V}_T	+	0.021	8–11
\dot{V}_A	+	0.051	8–11
$\dot{V}/\dot{V}O_2$	–	0.003	8–11
$\dot{V}/\dot{V}CO_2$	–	0.003	8–11
$PAco_2$	–	0.005	8–11
$P\bar{V}CO_2$	–	0.038	8–11
tcPco ₂	–	0.002	20–23
tcPo ₂	+	0.008	8–11
f_C	+	0.005	20–23
<i>Q</i>	+	0.017	8–11
\dot{Q}/f_C	+	0.017	8–11
\dot{Q}/weight	+	0.017	8–11
f_C/weight	+	0.070	8–11
Blood pressure			
Systolic	–	0.056	20–23
Diastolic	–	0.021	8–11
Mean arterial	–	0.022	8–11

* (+) indicates increase, (–) indicates decrease.

For abbreviations see Abbreviations section on p. iv.

9. General discussion of cardiopulmonary adaptation during rest

This is a longitudinal study which focuses on both the inter- and intra-individual changes during pregnancy. The women were sitting on the ergometer during the rest period, thereby creating a basis for the exercise. Also the risk of the caval compression syndrome repeatedly observed in supine women in late pregnancy was avoided or at least reduced.

Standing, late in pregnancy, leads to periodic accelerations in maternal heart rate due to restricted venous return from the lower limbs. A uterine contraction follows and venous return is temporarily restored. This is what Schneider *et al.* (1984) called 'the oscillating vena cava syndrome during quiet standing'. No such cyclical maternal heart rate waves were seen in this study.

When observing the effect of pregnancy, it is obvious that reliable non-pregnant points of reference are necessary. In many studies a control group has been used, but this precludes a longitudinal study which has the advantage of showing the inter-individual changes in detail. About a dozen longitudinal studies have been published. Their 'non-pregnant' baseline has been from a few days after delivery up to 12 months later. As we have found in virtually every variable investigated, the values at 6-8 weeks after delivery were somewhere in between those at term and those at 8-12 months after delivery. It follows that those authors who use 6 weeks post partum, or even earlier, as their non-pregnant level will find relatively smaller changes during pregnancy than we have found. Sadly *et al.* (1990) came to the same conclusion in their study of the cardiovascular response to cycle exercise in nine women at 26 weeks gestation and at 2 and 7 months post partum.

The puerperium is a dynamic period undoubtedly worth a special study of its own as both the intra- and inter-individual variations are marked. In the gas exchange and in some of the respiratory variables the median levels were similar to those at term, but P_{aCO_2} and P_{vCO_2} were already rising in the direction of the non-pregnant levels. Most pronounced of the changes noted in the puerperium was the drop in heart rate. As cardiac output was higher than in the last months of pregnancy, stroke volume and oxygen pulse showed peak values during the puerperium.

It would be tempting to attribute the higher values at 6 weeks post partum to lactation. However, Robson *et al.* (1989) found no differences in heart rate, stroke volume, cardiac output or blood pressure in 17 lactating mothers compared with 13 non-lactating mothers at 2, 6, 10 and 14 days after delivery. Because of these results we conclude that the absorption of superfluous tissue and the restitution of a non-pregnant metabolism takes more than 6-8 weeks, and that lactation, if present, is only one of the extra energy requirements at this time.

Taking the results obtained at 8-12 months after delivery as the non-pregnant level does not indicate accurately the pregnancy increment. The weight of women a year after childbirth is usually higher than before. This to some extent explains why weight only increased significantly at 20 weeks, but the result is in the same direction as found by Dawes & Grudzinkas (1991) who studied maternal weight in 1145 pregnant women. Their average weekly weight gain from booking to 16 weeks was 0.31 kg compared with about 0.50 kg later in pregnancy. The early increase in plasma volume, in this study demonstrated by the decreased haematocrit (Fig. 9.1) and haemoglobin concentration (Fig. 9.2), indicates water retention and an early weight gain. The other variables likely to be influenced by the use of a somewhat too high non-pregnant weight such as $\dot{V}O_2$, $\dot{V}CO_2$, \dot{V} etc. would be less affected than the weight itself and, if anything, the changes seen between the pre-pregnant period and 8-11 weeks gestation would have been somewhat higher than given here.

It would seem logical to explain the primary cause and then to illustrate the consequences of this in the various variables studied. However, the only primary cause is pregnancy itself, and this results in such marked changes in circulation and respiration and in the hormonal milieu that it is questionable whether it is justified to speak of any other primary cause or causes.

Except for weight gain, which only becomes obvious at about 20 weeks gestation, all the variables studied at 8-11 weeks were different from the non-pregnant state. Schematically there were six outstanding and only partially inter-dependent changes during pregnancy:

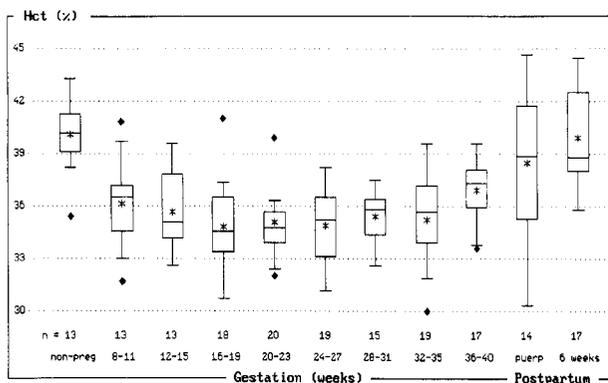


Fig. 9.1. 'Box and whisker' plot of haematocrit.

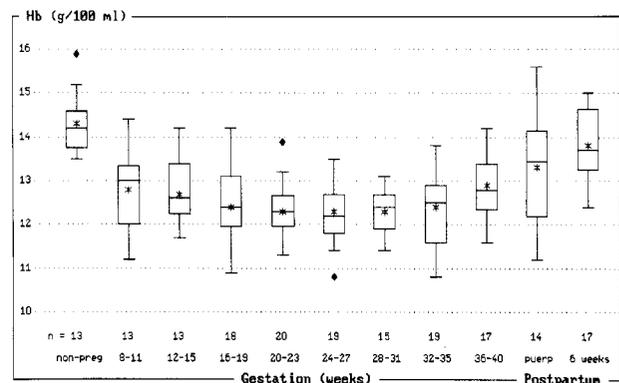


Fig. 9.2. 'Box and whisker' plot of haemoglobin concentration.

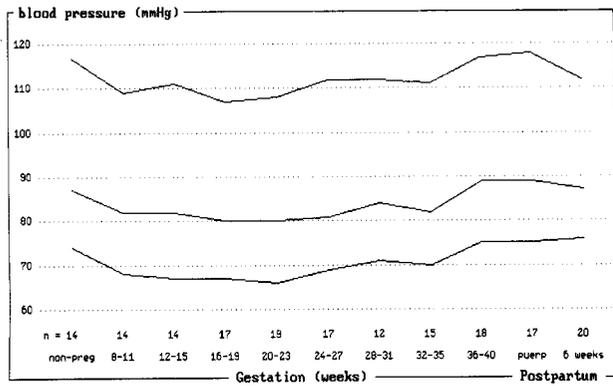


Fig. 9.3. Read from top to bottom: median systolic, mean arterial and diastolic blood pressure.

- (1) hyperventilation,
- (2) increase in the circulating plasma volume;
- (3) fall in peripheral resistance;
- (4) shunt-like circulation in the kidney and in the placenta;
- (5) increase in $\dot{V}O_2$ as more oxygen is needed for making and supplying new maternal and fetal tissues and for such changes in the metabolism as the large increase in sodium reabsorption;
- (6) increase in body temperature.

The total $\dot{V}O_2$ increase during pregnancy is due to at least all these six factors together.

$\dot{V}O_2$ increased by some 40% at the first study period compared with the non-pregnant level, and then only rose slowly *pari passu* with the weight increase. Taking into account the fact that part of the total water increase consumes no oxygen, there was some gradual increase in $\dot{V}O_2$ /weight throughout pregnancy. Teleologically this makes sense since more active fetal and placental tissue are synthesized, maternal fat deposits made, etc.

According to Metcalfe *et al.* (1981) about half of the increase in $\dot{V}O_2$ may be attributed to the growth and metabolism of the fetus, uterus and placenta, and the rest to increased work of the maternal myocardium, respiratory muscles and kidneys as well as other maternal tissue growth and development, mainly the breasts. The hyperventilation is seen in the fall in $PACo_2$ and $P\bar{V}co_2$. Furthermore, following the onset of pregnancy, body temperature is increased by approxi-

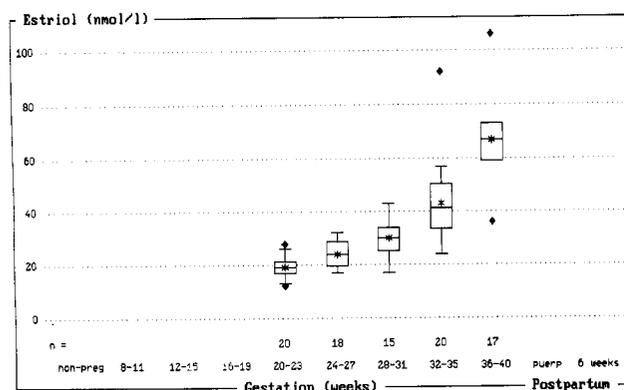


Fig. 9.4. 'Box and whisker' plot of oestriol plasma concentration.

mately 0.5°C until mid-gestation (Artal & Wiswell 1986). As 1°C increases $\dot{V}O_2$ by about 13%, this would explain some of the initial increase in $\dot{V}O_2$.

Almost all previous studies agree that $\dot{V}O_2$ increases, but some hold the opinion that there is only an initial rise; others consider that there is a further increase. The great variability seen in individual women largely explains these differences of opinion. The picture just described refers to the median in our studies, and to mean values in other studies, but only occasionally to the individual woman. On the whole, it is better to compare our median values, or the 25th-75th centiles, as in the boxes, with reviews such as those by Hytten & Chamberlain (1980) or Lotgering *et al.* (1985) as so few other studies are longitudinal and the individual variation is large.

Two factors call for increased ventilation: the higher oxygen consumption due to pregnancy and the hyperventilation needed to keep Pco_2 at the lower, pregnant, level. \dot{V} increases but respiratory rate tends to decrease; consequently, tidal volume increases and raises alveolar ventilation. The increase in the latter is one of the most characteristic features of cardiopulmonary adaptation to pregnancy.

As there were no statistically significant changes in RQ during the course of the study, no further comment is needed.

It is the function of the circulatory system to provide the tissues with oxygen. It would, therefore, be expected that cardiac output could mirror the $\dot{V}O_2$ changes. Although there are similarities, there is one important difference: a peak level of \dot{Q} was reached between 12 and 15 weeks gestation, but thereafter no major changes were seen. This is noteworthy as \dot{Q} usually changes with $\dot{V}O_2$. It would therefore be expected that \dot{Q} would increase, as does $\dot{V}O_2$, towards term. This becomes even more manifest when expressed as \dot{Q} /weight as there was a distinct decrease in the median value throughout the remaining gestation. If we assume that part of the 7 kg of water increase does not call for a corresponding increase in cardiac output, then the fall in \dot{Q} would be less pronounced than it is. Thus, the implication of our observation is that somehow the circulation becomes gradually more effective from the 16th week. It could be compared to training.

The abrupt increase in \dot{Q} by the first measurement in pregnancy was mainly due to an increase in stroke volume, the median values rising from 35 to 50 ml for the rest of the pregnancy. The larger stroke volume resulted in a larger oxygen pulse which rose sharply by 8-11 weeks gestation. Only late in the last month of pregnancy was there a tendency to a further

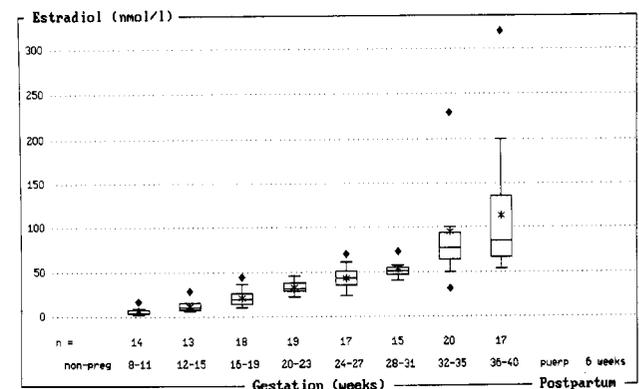


Fig. 9.5. 'Box and whisker' plot of oestradiol plasma concentration.

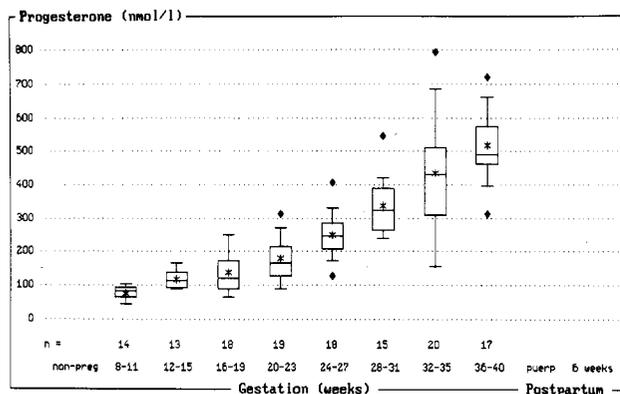


Fig. 9.6. 'Box and whisker' plot of progesterone plasma concentration.

increase in $\dot{V}O_2/f_C$. Thus, looking at the oxygen pulse as an indicator of training, it is difficult to imagine that pregnancy could induce a training effect as early as before 8–11 weeks. The further increase in the last month could be seen in this light.

Results from the earliest studies were presented in the form of tables so that the individual variations could be traced. Recent studies give little attention to this, with the exception of Knuttgen & Emerson (1974) and Pernoll *et al.* (1975). Both groups stated the number of women who did not follow the general pattern. In the present study the individual changes have been illustrated systematically.

Both the inter- and intra-individual variations were considerable. The dominant feature of the inter-individual differences was the stratification: if, for instance, $\dot{V}O_2$ was low in the first test it tended to be low also in the subsequent studies. Obviously weight was dominant as a variable ranging between

42 and 100 kg but, even after standardizing for weight, the intra-individual variability was large. Both during and after pregnancy the intra-individual curves varied for most variables, and this could partly explain the different results published by different authors. However, $\dot{V}/\dot{V}O_2$, $\dot{V}/\dot{V}CO_2$, $PACO_2$, $P\bar{V}CO_2$ and $tcPco_2$ decreased in all the women when they became pregnant.

The pregnancy changes were already obvious by 8–11 weeks gestation. The fall in haematocrit (Fig. 9.1) and haemoglobin concentration (Fig. 9.2) shows that the circulating plasma volume had increased by about 10%. This would explain, at least in part, the cardiac and pulmonary changes. Mean and diastolic blood pressure also fell significantly (Table 3, see p. 21, and Fig. 9.3).

It is futile to try to attribute the changes to any, or even several, of the known hormones that increase during pregnancy. Rather, the adaptation to pregnancy is caused by an intricate resetting of the hormonal balance which changes continuously as pregnancy progresses. Nisell *et al.* (1985) showed that in normal pregnancy the adreno-medullary activity is reduced. The higher oestrogen concentration (De Swiet 1980a) will probably increase cardiac output and lower systemic vascular resistance, although there is a continuous increase in the oestrogen concentration (as seen in Figs 9.4 and 9.5) but not in cardiac output.

A parallel argument could be used for progesterone (Fig. 9.6). A similar conclusion was drawn by Lewis *et al.* (1980), who showed that the concentration of the important vasodilator prostacycline increases during pregnancy, although there was no parallel fall in blood pressure. Thus, it seems that while all the hormones are presumably important in the overall conduct of the pregnant state, in none of them is there any simple, quantitative relation between concentration and response.

10. Cardiopulmonary adaptation during exercise

10.1 General aspects

During rest and the two exercise periods at light and moderate work respectively, most of the variables studied showed changes similar to those illustrated in Fig. 10.1. The initial rest level is that described in Chapters 3-8. The steady-state levels at the end of each working period are the basis of the individual values. To show the changes due to the workloads and unaffected by the changes in the course of pregnancy, the increases over and above the resting levels are presented for light and moderate work. Median curves, of the same type as used previously, are given for both workloads. As they are superimposed as seen first in Fig. 10.2, the 'box and whisker' plots cannot be used. A few variables did not show steady-state levels at the end of the working periods. In such cases plots of the same type as illustrated in Fig. 10.1 are given to show the values during each 30-s period for the non-pregnant women, those at 8-11 weeks gestation and those at 36-40 weeks. The individual curves are given for moderate work.

10.2 Oxygen consumption

Figure 10.2 shows that during light work the median $\dot{V}O_2$ increase was 420 ml/min in the non-pregnant women compared with 510 ml/min at 12-15 weeks gestation. At mid-pregnancy $\Delta \dot{V}O_2$ had decreased to 460 ml/min and a peak of 540 ml/min was seen at term. During moderate work the increase was more abrupt: $\Delta \dot{V}O_2$ increased from 710 ml/min in the non-pregnant women to 840 ml/min by 8-11 weeks gestation, a statistically significant difference. A plateau of

about 800 ml/min was seen in mid-pregnancy and a peak of 890 ml/min at term.

In general the individual curves for the 60-W workload (Fig. 10.3) showed parallel changes similar to those of the median. All women showed the initial increase in $\Delta \dot{V}O_2$, but only seven had a decrease at mid-pregnancy. The increase until term was more consistent with only three exceptions. The individual values of $\Delta \dot{V}O_2$ varied between 650 ml/min and 1100 ml/min in the non-pregnant and between 960 and 1320 ml/min at term.

Figure 10.4 shows the absolute values during moderate work. The pattern is similar to that seen in Fig. 10.3, but the levels are higher.

Discussion

Figure 3.3 shows that oxygen consumption increased by about 40% in early pregnancy compared with the non-pregnant level. Taking Figs 3.2 and 10.2 together, it follows that during pregnancy and exercise $\dot{V}O_2$ is increased for three reasons: pregnancy itself, exercise as such, and the combination of pregnancy and exercise.

As the bicycle exercise is not weight dependent, it could be assumed that additional oxygen needed during work would show less inter-individual variation than the absolute $\dot{V}O_2$ values. It will be seen, comparing the individual curves shown in Figs 10.3 and 10.4, that this is not so. The same stratification is present in both figures, and individual patterns are similar. The oxygen supply to the tissues is the most important variable to study when investigating the adaptation to pregnancy at rest and during exercise. Only by monitoring $\dot{V}O_2$ can we follow the changing maternal and fetal energy requirements. Augmentation in ventilation and circulation are needed to increase $\dot{V}O_2$ and oxygen delivery to the tissues.

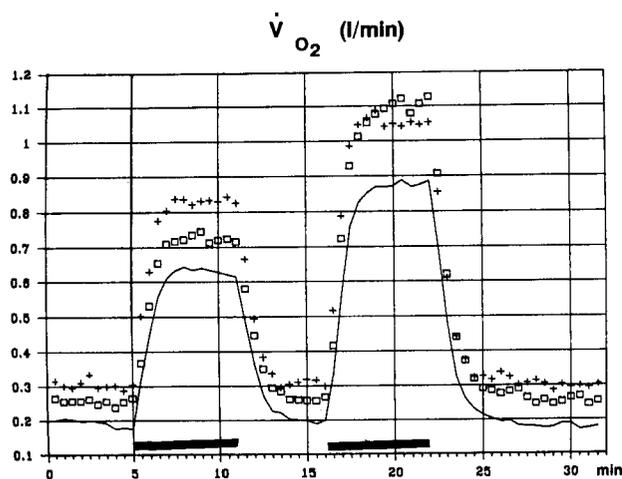


Fig. 10.1. Mean oxygen consumption during each 30-s period during rest, light work (min 5-11), further rest, moderate work (min 16-22) and a recovery period in (-) non-pregnant women, (□) at 12 weeks and (+) at 40 weeks gestation.

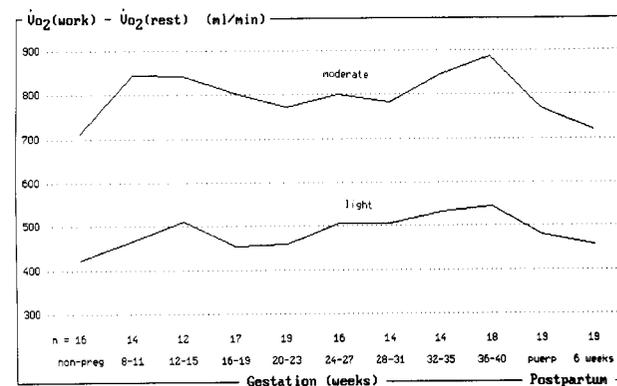


Fig. 10.2. Median increase in oxygen consumption during light and moderate work compared to resting levels.

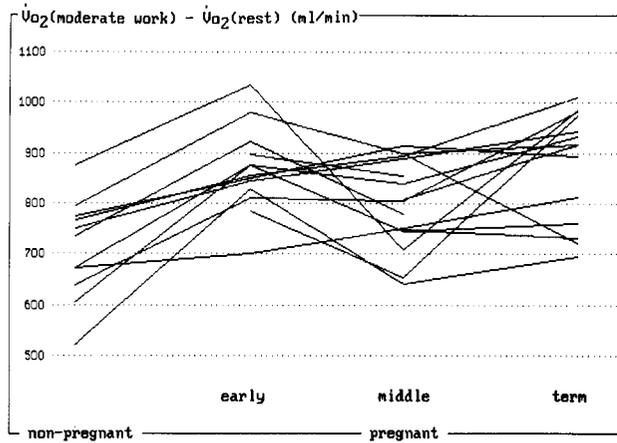


Fig. 10.3. Individual increases in oxygen consumption during moderate work compared with resting levels.

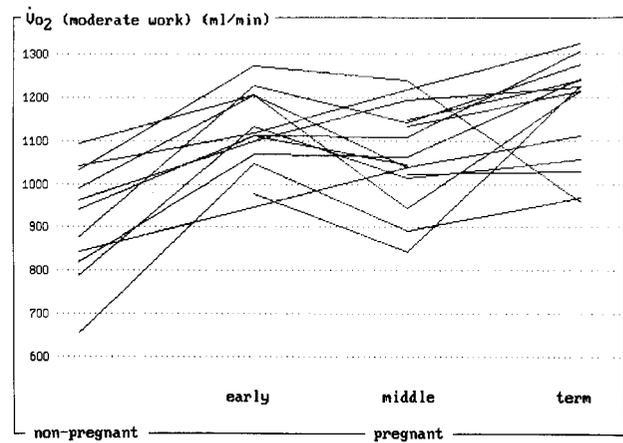


Fig. 10.4. Individual oxygen consumption during moderate work.

Although important and often limiting factors, they are secondary to the oxygen demands of the tissues.

Some authors such as Wiswell (1986) and others prefer to express the workload in 'metabolic equivalents' (MET) with resting $\dot{V}O_2$ taken as one. As $\dot{V}O_2$ during light work was about three times that at rest, this corresponds to 3 MET. Moderate work was somewhat above 4 MET.

Our results are basically in accordance with, among others, those of Schweingel & Lauckner (1984), Pernoll *et al.* (1975), Lehmann & Regnat (1976), and Edwards *et al.* (1981). Guzman & Caplan (1970) found that, for a given workload, $\dot{V}O_2$ was the same 12 weeks after delivery as during pregnancy. By contrast, they found that \dot{V} , f_c and Q were always higher during pregnancy. Artal *et al.* (1986a) reported higher oxygen consumption in pregnant than in non-pregnant women at rest and during mild exercise, whereas they found the reverse during moderate and maximal treadmill exercise.

Pernoll *et al.* (1975), using bicycle ergometry, found for the same workload an increased $\dot{V}O_2$ late in pregnancy and described this as reduced efficiency, which will be further analysed in Chapter 15. Like Pernoll *et al.* (1975), we have no obvious explanation for these observations, only speculations. During work, the pregnant woman is only restricted in her activity after she has begun to gain weight

and the size of the uterus restricts normal movements. We wondered whether the different response to moderate work could be due to the protocol of the exercise tests in which light work preceded moderate work. Perhaps some of the adaptation to work entrained during the light work was carried over to improve the results seen during moderate work. Such a hypothesis would agree with the observation by Lehmann & Regnat (1976) that the circulation adapts more slowly to changes during pregnancy. Two additional factors should be considered: first, the fact that in six of the pregnant women moderate work was reduced to 50 instead of 60 W from mid-pregnancy, and second, that work efficiency during moderate work is better than during light work. These points will be discussed in Chapter 15.

10.3 Carbon dioxide production

It will be seen in Fig. 10.5 that the increases in $\dot{V}CO_2$ during light and moderate work are similar to those illustrated in Fig. 10.2 for oxygen, except that the peak value during moderate work occurred at 12–15 weeks gestation. The individual curves (Fig. 10.6) also resemble those for $\Delta\dot{V}CO_2$. The initial increase in $\Delta\dot{V}CO_2$ was statistically significant.

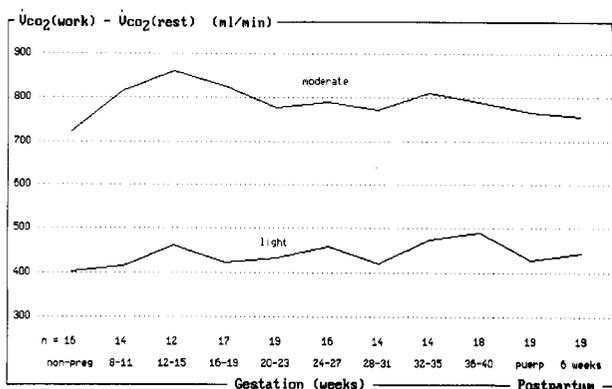


Fig. 10.5. Median increase in carbon dioxide production during light and moderate work compared with resting levels.

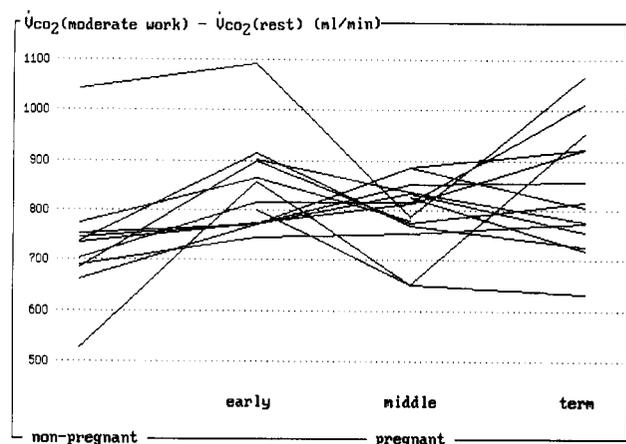


Fig. 10.6. Individual increases in carbon dioxide production during moderate work compared with resting levels.

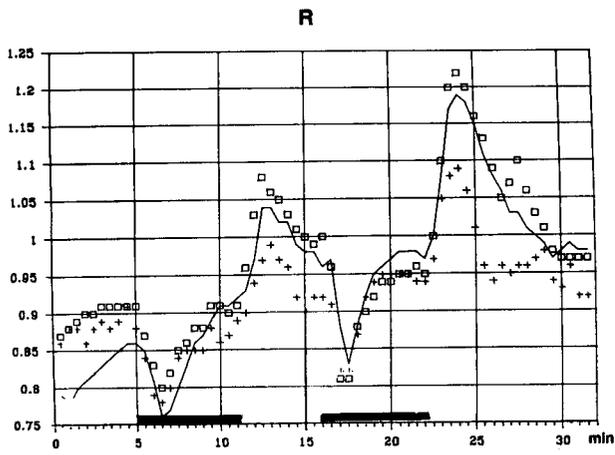


Fig. 10.7. Mean respiratory exchange ratio during each 30-s period during rest, light work (min 5–11), further rest, moderate work (min 16–22) and recovery period in (–) non-pregnant women, (□) at 12 weeks and (+) at 40 weeks gestation.

10.4 Respiratory exchange ratio (R)

Although the $\Delta\dot{V}O_2$ and $\Delta\dot{V}CO_2$ curves all look similar, and apparently a plateau was reached for each variable during the last minutes of exercise (see Fig. 10.1), the more sensitive respiratory exchange ratio (R), $\dot{V}CO_2/\dot{V}O_2$, did not show any plateau and is certainly no indicator for the metabolic RQ (Fig. 10.7). As will be seen, R first decreased during the onset of the exercise periods and then gradually increased with a peak about 2 min after the end of the exercise.

Discussion

The main reason for the difference between RQ in Chapter 3.4 and R is that oxygen consumption increases rapidly during exercise, but there is a delay of about 2 min before the corresponding carbon dioxide appears in the expired air. Furthermore, there are several complex changes between the intra- and extra-cellular carbon dioxide during exercise.

11. Ventilation

11.1 Ventilation per minute

Figure 11.1 shows the median increase in \dot{V} during light and moderate work. Both curves showed a peak at term and a distinct fall in the puerperium. The difference between the two workloads was that during light work there was a plateau of about 12 l/min in the non-pregnant state which remained until mid-pregnancy when the increase towards term had reached 15.7 l/min. At moderate work the median increase was 20.8 l/min in the non-pregnant women, rising significantly to 22 l/min at 8-11 weeks gestation, attaining a plateau of about 24 l/min at 12-15 weeks, with a peak of 25.5 l/min at term.

The individual women (Fig. 11.2) had non-pregnant values for $\Delta\dot{V}$ of between 16 and 24 l/min. At term the corresponding range was 20-33 l/min. The exception was one woman in whom $\Delta\dot{V}$ increased from 32 l/min in the non-pregnant state to 50 l/min at term. Four women showed a decrease in $\Delta\dot{V}$ from mid-pregnancy to term.

11.2 Respiratory rate

Figure 11.3 illustrates the increase in respiratory rate due to exercise. During light work the non-pregnant women increased their rate by a median of 4.5 breaths/min. During pregnancy there was an increase up to about 7 breaths/min at term and a rapid return to normal in the puerperium. Parallel changes were seen during moderate work, but the lowest median increase of 7 breaths/min was noted not only in the non-pregnant women but also at 8-11 and at 20-23 weeks gestation and in the puerperium. The peak values were 8.5 breaths/min at 12-15 weeks and after 28 weeks. Thus, there were no significant differences in the median values for Δf_R between the non-pregnant and the pregnant women during moderate work.

As will be seen from the individual graphs (Fig. 11.4), there

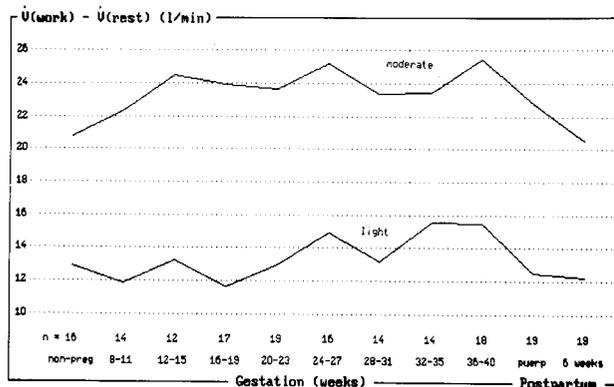


Fig. 11.1. Median increase in ventilation during light and moderate work compared with resting levels.

was an extremely wide range of increase in respiratory rate from 1 to 18 breaths/min in the non-pregnant women. At term the range was 5-18 breaths/min. No dominant pattern was present. Between any of the two time periods there might be an increase or decrease in Δf_R .

11.3 Tidal volume

Median tidal volume (Fig. 11.5) increased by 400 ml during light work in the non-pregnant women and more or less stayed at that level except at 12-15 and at 36-40 weeks gestation when tidal volume had increased by 480 ml. During moderate work median tidal volume had increased by 670 ml in the non-pregnant women. Early in pregnancy the tidal volume had increased by 800 ml, which was statistically significant, but from 16 weeks gestation ΔV_T stayed at about 700 ml.

Individual variations in ΔV_T values during moderate work ranged between 340 and 830 ml in the non-pregnant women, and between 540 and 1170 ml at term. Except for four women, ΔV_T increased when the women became pregnant and all except two showed higher ΔV_T at term than in mid-pregnancy (Fig. 11.6).

11.4 Alveolar ventilation

Median alveolar ventilation increased by 7.5 l/min when the non-pregnant women performed at 30 W on the ergometer (Fig. 11.7). During pregnancy the increase associated with light work rose to 11.5 l/min at term and returned to the non-pregnant value in the puerperium. During 60 W of exercise, $\Delta \dot{V}_A$ was 13.6 l/min in the non-pregnant women and had already increased to 18 l/min by 8-11 weeks gestation, remaining at this level throughout the rest of the pregnancy (the difference was statistically significant).

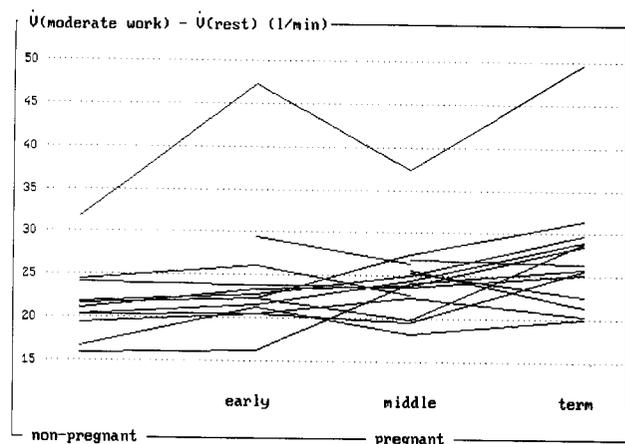


Fig. 11.2. Individual increase in ventilation during light and moderate work compared with resting levels.

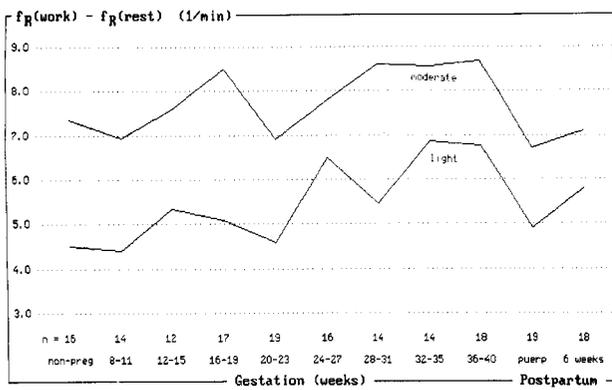


Fig. 11.3. Median increase in respiratory rate during light and moderate work compared with resting levels.

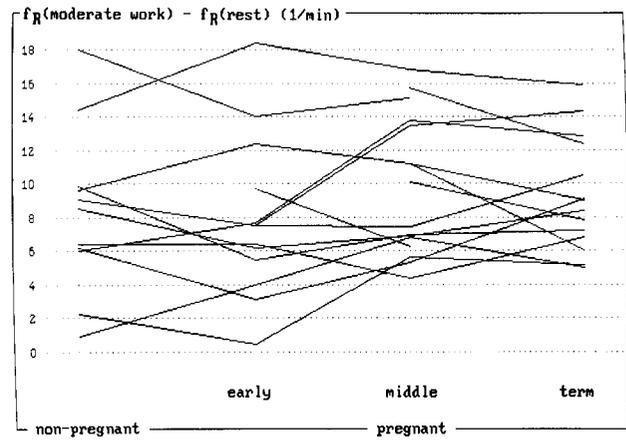


Fig. 11.4. Individual increase in respiratory rate during moderate work compared with resting levels.

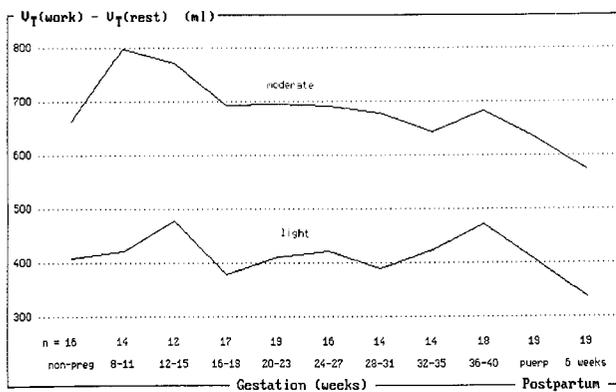


Fig. 11.5. Median increase in tidal volume during light and moderate work compared with resting levels.

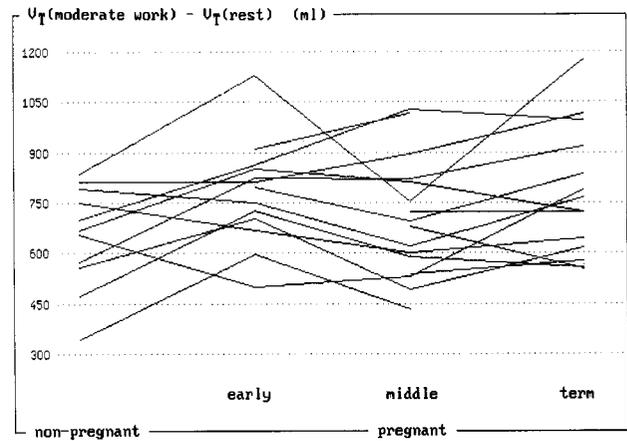


Fig. 11.6. Individual increase in tidal volume during moderate work compared with resting levels.

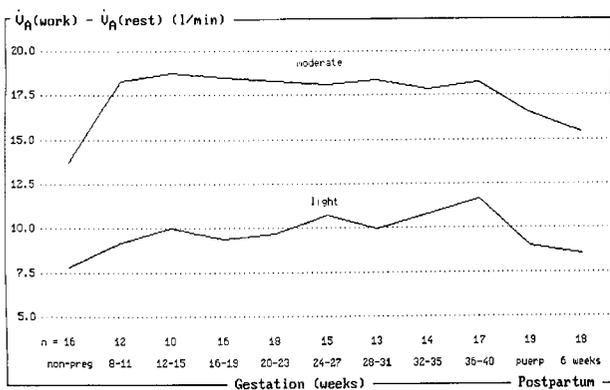


Fig. 11.7. Median increase in alveolar ventilation during light and moderate work compared with resting levels.

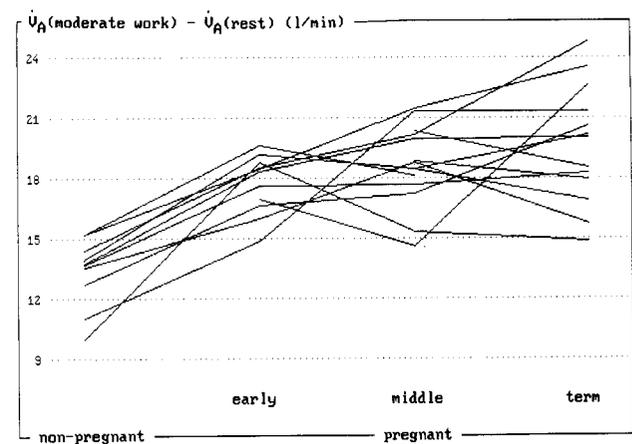


Fig. 11.8. Individual increase in alveolar ventilation during moderate work compared with resting levels.

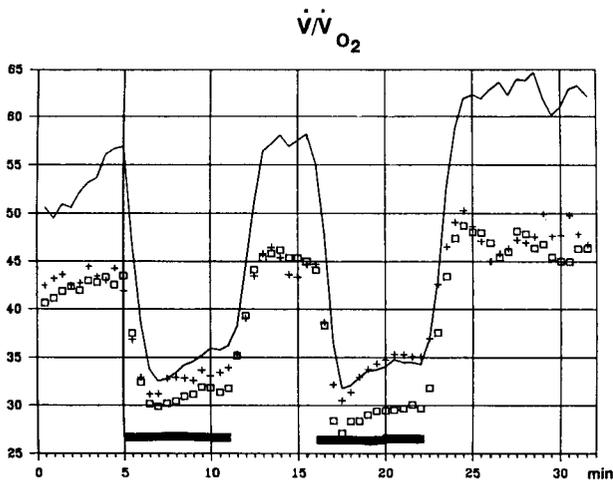


Fig. 11.9. Mean ventilatory equivalent for oxygen during each 30-s period during rest, light work (min 5–11), further rest, moderate work (min 16–22) and a recovery period in (–) non-pregnant women, (□) at 12 weeks and (+) at 40 weeks gestation.

The individual levels varied markedly, but the patterns of change were on the whole consistent in contrast to the individual changes in respiratory rate or tidal volume. In all women the increase in alveolar ventilation was higher early in pregnancy than in the non-pregnant state. Thereafter both a rise and a fall in the individual curves were found, the net result being the plateau described above. At term, $\Delta\dot{V}_A$ was higher in all women than 8–12 months later, our non-pregnant time period (Fig. 11.8).

Discussion

In Chapter 4 it was shown that the increased ventilation during early pregnancy was achieved by an increase in tidal volume, and that respiratory rate was actually lower than in the non-pregnant state. During work ventilation needs to be further increased, and Δf_R was similarly increased for both workloads in the non-pregnant women and at 8–11 weeks gestation, but later in pregnancy an additional increase in Δf_R contributed to the increased ventilation.

The intra-individual patterns varied markedly and neither respiratory rate nor tidal volume can be studied separately to represent ventilation adequately, even if these two variables changed without any distinctive pattern. When the respiratory rate was high the tidal volume was less pronounced, and vice versa. For example, the respiratory rate increased between 1 and 18 breaths in the non-pregnant women during moderate work. Thus, during work, one woman may increase her alveolar ventilation by increasing the respiratory rate, whereas another woman will do so by increasing her tidal volume. To perform the work, \dot{V} and \dot{V}_A had to increase and, consequently, the changes in these variables were more consistent.

Pernoll *et al.* (1975) found that during pregnancy the excess \dot{V} due to a workload of 50 W was about 20%. They found a mean \dot{V}_A of 27 l/min during bicycle exercise, and we found median values of about 25 l/min.

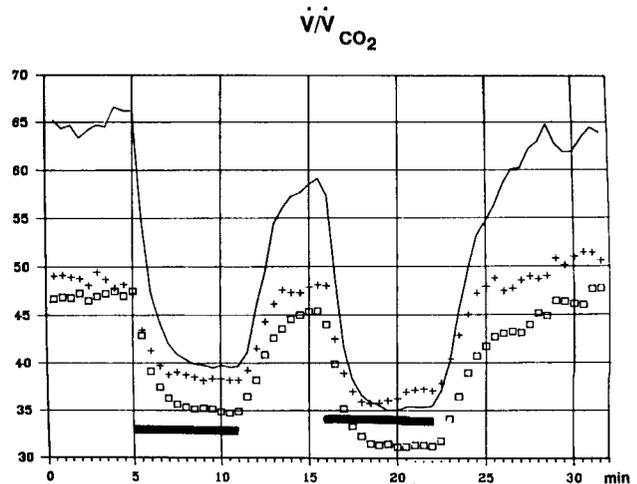


Fig. 11.10. Mean ventilatory equivalent for carbon dioxide during each 30-s period during rest, light work (min 5–11), further rest, moderate work (min 16–22) and a recovery period in (–) non-pregnant women, (□) at 12 weeks and (+) at 40 weeks gestation.

11.5 Ventilation equivalents

As no clear indications of steady-state levels were seen in either the equivalent for oxygen or for carbon dioxide, Figs 11.9 and 11.10 are of the same type as shown in Fig. 10.1 where the means of all the women at all measuring points produce curves that resemble those seen during the actual tests. Both the \dot{V}/\dot{V}_{O_2} and the \dot{V}/\dot{V}_{CO_2} curves are of similar shape with marked decreases once exercise begins. During exercise the lowest values for \dot{V}/\dot{V}_{O_2} of about 32 were seen in the non-pregnant women as well as in those at term, and were down to 30 at 8–11 weeks gestation.

Mean \dot{V}/\dot{V}_{CO_2} in the non-pregnant women and in those at term decreased to 38–39 during light work and to 30–32 during moderate work. At 8–11 weeks gestation the nadir was 35 during light work and 32 during moderate work.

Discussion

As discussed in Chapter 4.2, the reduced ventilatory equivalents for oxygen and carbon dioxide indicate improved gas exchange at rest during pregnancy. Because of the higher levels of \dot{V}/\dot{V}_{O_2} and \dot{V}/\dot{V}_{CO_2} in the non-pregnant than in the pregnant women, the fall was less pronounced during exercise in pregnancy. Both ventilatory equivalents were lowest at 8–11 weeks gestation; in the non-pregnant women and at term they were more or less equal. Accepting the ventilatory equivalents as indicators of the cardiopulmonary adaptability to exercise (Mellerowicz & Nowacki 1961), this was optimal at 8–11 weeks gestation. The difference between values at 8–11 weeks and at term might be caused by some restriction in breathing due to the large uterus in late pregnancy, thereby counteracting the better gas exchange at rest.

12. Alveolar Pco₂

As can be seen in Fig. 12.1, ΔP_{Aco_2} was 0.5–0.7 kPa (4–5 mmHg) higher during exercise than at rest in the non-pregnant women. *Pari passu* with the progress of pregnancy, this difference was reduced only to increase again in the puerperium. The median curves for light and moderate exercise were similar. P_{Aco_2} during moderate work ranged from 4.7 to 5.7 kPa (36 to 43 mmHg) in the non-pregnant women and from 4.0 to 4.5 kPa (30 to 34 mmHg) during pregnancy.

The individual curves showed a wide range (Fig. 12.2) but were mostly parallel, the only difference being that in some of the pregnant women ΔP_{Aco_2} was already reduced in early pregnancy, and in others in mid-pregnancy.

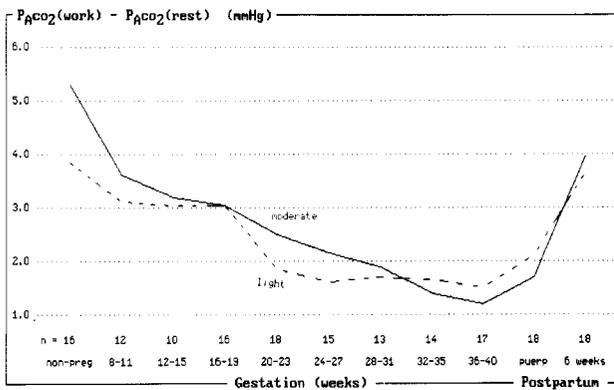


Fig. 12.1. Median changes in alveolar Pco₂ during light and moderate work compared with resting levels.

Discussion

Wasserman & Whipp (1975) showed that P_{Aco_2} was higher than P_{aco_2} during exercise. Lehmann & Regnat (1976) saw no change in maternal P_{aco_2} during work at 50 W, whereas end-expiratory P_{co_2} increased. Pernoll *et al.* (1975) found the difference in their mean P_{Aco_2} between rest and exercise to be about 1.1 kPa (8 mmHg) 5–8 weeks after delivery, and about 0.5 kPa (4 mmHg) during pregnancy. In non-pregnant women and in early pregnancy we found similar values, but gradually the difference was reduced as pregnancy progressed. The mechanism behind this is obscure.

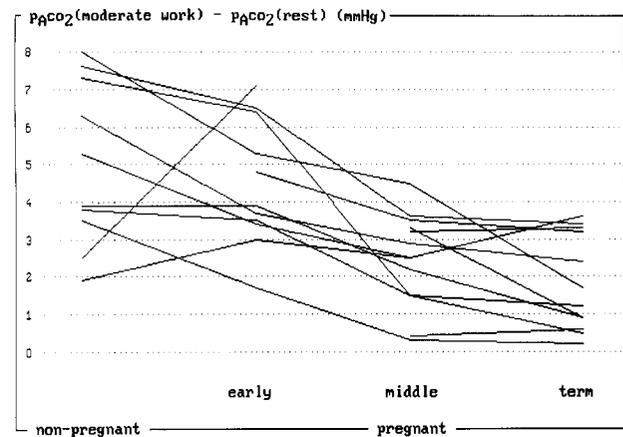


Fig. 12.2. Individual changes in alveolar Pco₂ during moderate work compared with resting levels.

13. Transcutaneous Pco₂ and transcutaneous Po₂

Figure 13.1 shows the systematic tcPco₂ changes during rest and exercise (the mean values for all women are shown at 30-s time periods during rest and exercise). Moving in the same direction as PAcO₂, tcPco₂ was higher during work than at rest. Later in pregnancy this difference was reduced. The initial levels, as discussed in Chapter 6, were highest in the non-pregnant women.

Figure 13.2 shows the systematic changes of tcPo₂ caused by the exercise. Immediately after the onset of work, tcPo₂ decreased by about 0.3 kPa (2–3 mmHg). After 2 min tcPo₂ increased and continued to do so until 2 min after the end of exercise. The directions of the changes were equal in the non-pregnant and in the pregnant women, but the amplitude was increased during pregnancy and was also higher in late pregnancy than at 12 weeks gestation.

Discussion

Only a few continuous Po₂ studies have been published (Fabel 1968; Huch *et al.* 1974) and none for Pco₂. Using an intra-arterial Po₂ electrode, Fabel (1968) demonstrated qualitatively similar changes to our findings for tcPo₂. The initial fall in Po₂, whether expressed as Pao₂ or tcPo₂, indicates that the initial oxygen demand is not immediately compensated for by the increased ventilation. The further increase during rest is a sign of the persistent hyperventilation due to the oxygen debt.

The changes in tcPco₂ are logically similar to those seen for tcPo₂, but of course in the opposite direction. Furthermore, they are more delayed and dampened because of the longer response time of the tcPco₂ than of the tcPo₂ electrode. The transcutaneous values are 20–50 s later than the arterial values (Huch *et al.* 1981).

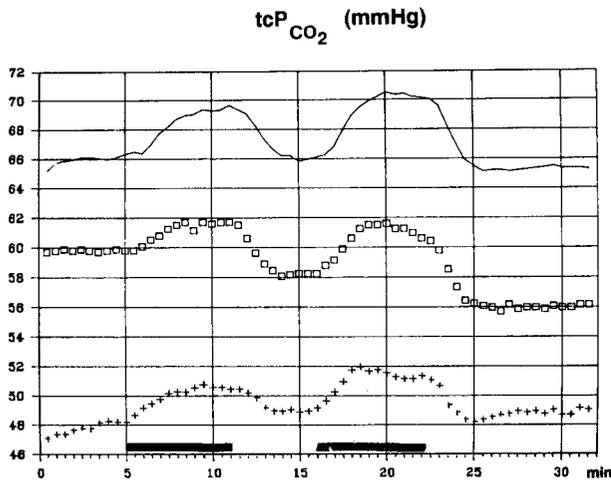


Fig. 13.1. Mean transcutaneous carbon dioxide pressure during each 30-s period during rest, light work (min 5–11), further rest, moderate work (min 16–22) and a recovery period in (–) non-pregnant women, (□) at 12 weeks and (+) at 40 weeks gestation.

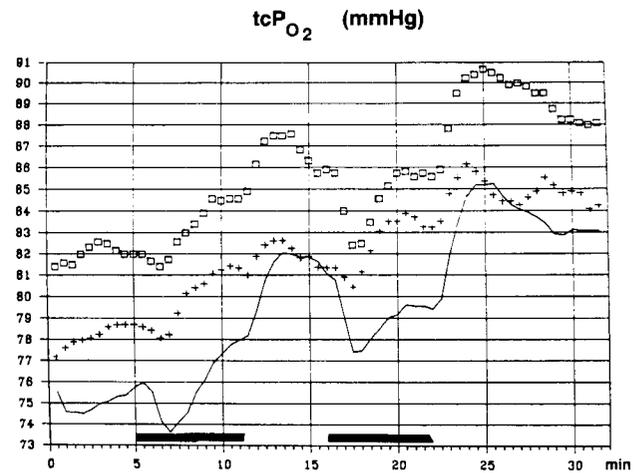


Fig. 13.2. Mean transcutaneous oxygen pressure during each 30-s period during rest, light work (min 5–11), further rest, moderate work (min 16–22) and a recovery period in (–) non-pregnant women, (□) at 12 weeks and (+) at 40 weeks gestation.

14. Circulation

14.1 Heart rate

In the non-pregnant women the median increase in heart rate during light work was 24 b.p.m. (Fig. 14.1). With minor variations this level was maintained until 28 weeks gestation when it began to decrease, reaching a nadir of 19 b.p.m. at 32-35 weeks gestation. At term, in the puerperium and at 6-8 weeks post partum the Δ heart rate was again about 27 b.p.m. During moderate work the increase varied more. In the non-pregnant women the median Δf_c was 45 b.p.m. and remained at that level at 8-11 weeks gestation. There was then an increase to 50 b.p.m. followed by a gradual decrease, here also with the lowest level at 31 b.p.m. at 32-35 weeks gestation. In the puerperium Δ heart rate was again higher with a median value of 49 b.p.m.

The individual curves showed a wide spread (Fig. 14.2). Δf_c ranged between 31 and 67 b.p.m. in the non-pregnant women during moderate work, and between 16 and 75 b.p.m. at term. The curves were superimposed in the non-pregnant state and at the beginning of pregnancy. Thereafter some women had a decrease and some an increase in Δf_c , and these changes occurred at different times. In four women the increase in heart rate in late pregnancy was higher than in mid-pregnancy.

Discussion

At rest there was a gradual increase in heart rate during the course of pregnancy as described in Chapter 7.1. In contrast the additional heart rate increase with exertion shows a different picture. There was of course an increase in heart rate during work, but light work seemed to be accomplished by the women with about the same increase in heart rate whether they were pregnant or not. The lower Δf_c during moderate work at 32-35 weeks gestation does not imply an actual decrease in heart rate at this time period because, as seen in Fig. 7.1, resting heart rate was then at a peak.

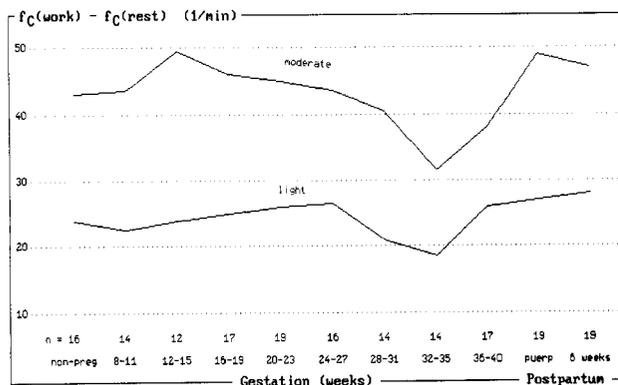


Fig. 14.1. Median increase in heart rate during light and moderate work compared with resting levels.

During moderate work the increase was more variable. In the last 2 months of pregnancy the workload was accomplished with a smaller increase in heart rate, which agrees with the results for $\dot{V}O_2$ in Chapter 9. Actually this point has been studied extensively. Lotgering *et al.* (1985) reviewed 25 human studies of the heart rate response to exercise; 14 of them found that, taking into account the heart rate increase due to pregnancy itself, the additional increase during exercise was similar in pregnant and non-pregnant women. However, only a few longitudinal studies have been reported, and the point in the present study is that heart rate acceleration during work was reduced only in late pregnancy.

Similar results have been reported by other authors such as Erkkola (1975), Kusche *et al.* (1986), and in the review by Wallace *et al.* (1986).

14.2 Oxygen pulse

The oxygen pulse increased during light work. As can be seen in Fig. 14.3, the increase was 3.5 ml in the non-pregnant women during light work, and 4.9 ml during moderate work. Early in pregnancy this rose to 3.7 and 5.4 ml during light and moderate work, respectively (the latter was statistically significant). In mid-pregnancy the same values were seen as in the non-pregnant women, and in late pregnancy the increases were 4.3 ml and 5.4 ml at light and moderate work, respectively. During the puerperium there was a marked fall in the curve. To express this another way, during light work oxygen pulse was at least 2.6 times higher than at rest, and it was at least 3.2 times higher during moderate work than at rest.

In general, individual curves were parallel (Fig. 14.4) but in one woman the minimum increase in oxygen pulse occurred in early pregnancy and in two women in late pregnancy.

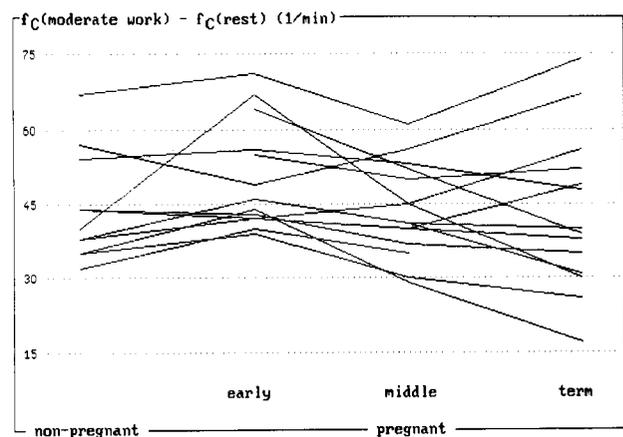


Fig. 14.2. Individual increase in heart rate during moderate work compared with resting levels.

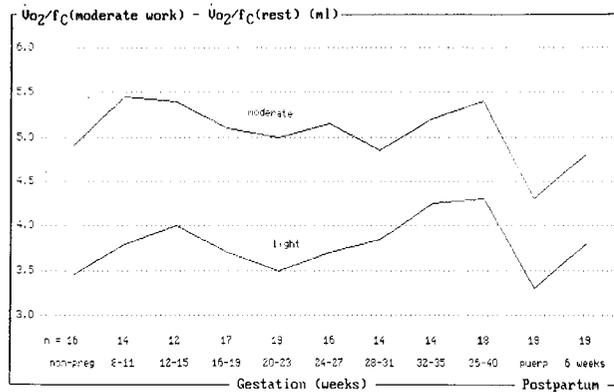


Fig. 14.3. Median increase in oxygen pulse during light and moderate work compared with resting levels.

Discussion

The indirect Fick method using rebreathing for determining $P\bar{V}CO_2$ cannot be used during work. Consequently, neither \dot{Q} nor stroke volume could be monitored, and therefore in the present study oxygen pulse and heart rate were the only two variables available for estimating cardiac function.

As oxygen pulse = stroke volume \times arterio-venous O_2 difference, stroke volume may be assessed if the arterio-venous O_2 difference is known. Guzman & Caplan (1970) found this to be 110 ml/l in non-pregnant women and 90 ml/l in pregnant women. Moreover, those arterio-venous differences were unaffected by the workloads. Using these values, stroke volume was 52 and 65 ml during light and moderate work, respectively, in non-pregnant women.

During the peaks seen in Fig. 14.3, stroke volume would be 77 ml during light work and 92 ml during moderate work. Guzman & Caplan (1970) found stroke volume to be 50 ml and 62 ml in non-pregnant women during a workload of 150

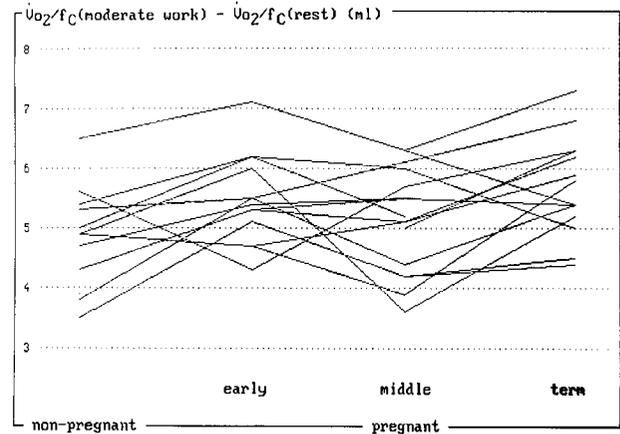


Fig. 14.4. Individual increase in oxygen pulse during moderate work compared with resting levels.

and 250 kg/min, respectively. During pregnancy their stroke volume increased to 60 and 72 ml during the two workloads. Similar results were published by Ueland *et al.* (1969). Sady *et al.* (1990) indicated that the arterio-venous oxygen difference was higher during exercise at 60 W than at 30 W. If this is so, the relation between the oxygen pulse and stroke volume is more complex, but even using the values reported by Sady *et al.* (1990), the direction of the changes would not be affected.

The main point of the above calculation was not to obtain absolute values but to study the direction of the changes. As suggested by Lotgering *et al.* (1985), during pregnancy there must be a larger increase in stroke volume during exercise. Our results support this. Furthermore, Fig. 14.3 indicates that in early and late pregnancy stroke volume during exercise is smaller than in mid-pregnancy. It is clear from Fig. 14.1 that cardiac output must be relatively smaller during moderate work from 32 weeks gestation than during early pregnancy.

15. Mechanical efficiency and statistical summary

The efficiency of work may be described in several ways. The usual way is to give the measured output of work as a percentage of the extra energy used to produce this work. When reading off 30 W on the bicycle ergometer, the extra energy being produced by the body is actually several times higher, because the human 'engine', like all mechanical devices, is less than 100% efficient.

For the calculation we have taken into account all the increased oxygen consumed during the 6 min of exercise, and also the excess oxygen consumed during the first 5 min of rest after light and 10 min after moderate work. As was shown in Fig. 10.1, the baseline was almost attained 5 min after light work.

In these calculations actual workload has been used. This is the only situation where the effect of the reduction in the workload from 60 to 50 W in six of the pregnant women may be quantified. It is obvious that $\dot{V}O_2$, $\dot{V}CO_2$, \dot{V} , and probably f_R and f_C also, would have been different and probably somewhat higher than the observed values if these women also had worked at 60 W in all the tests.

Figure 15.1 shows what may be called the 'physiological workload', the median of the extra energy expended for light and moderate work. Figure 15.2 illustrates the percentage efficiency. It will be seen that in the non-pregnant women the median efficiency was 20% at light work and 25% at moderate work. At 8-11 weeks gestation the median work efficiency was less than in the non-pregnant women during both light and moderate work (the latter difference was statistically significant). From mid-pregnancy there was a gradual fall, with a nadir at 32-35 weeks gestation and a rapid return to the non-pregnant level in the puerperium.

In general the individual lines were parallel. During moderate work (Fig. 15.3) the initial range was between 21 and 34%. With one exception there was, as during light work, a decrease in early pregnancy. In about half the women there was a rise at mid-pregnancy and then a fall in late pregnancy. In the others

the percentage efficiency remained at the same level for the rest of pregnancy. In one woman efficiency increased from early pregnancy until term.

Discussion

Hansen & Voss (1932) published the first reports of work efficiency during pregnancy. They found a mean value of 14.6% in pregnant women and 18.2% at 5-6 weeks post partum, the same directional change as in our study. Artal *et al.* (1986b) reported that some authors, such as Knuttgen & Emerson (1974), Pernoll *et al.* (1975) and Ueland *et al.* (1969) found a higher oxygen expenditure for a given work as pregnancy progressed, whereas Seitchik (1967) and Edwards *et al.* (1981) found no differences between the pregnant and non-pregnant women.

It will be seen that mechanical efficiency depends upon the workload. During the conditions of the exercise in these studies the efficiency was consistently about 5% higher at moderate than at light work. Had there been no increased mechanical efficiency at moderate work in mid-pregnancy, the women would have had a total energy expenditure of some 330 W instead of, as now, 250 W, as shown in Fig. 15.1.

The demonstration of the increased efficiency at moderate work compared to light work explains the relative small increase in $\dot{V}O_2$ when the workload was doubled, as indicated in Chapter 9.

Bung *et al.* (1988) studied a professional athlete using the same protocol and the same equipment as in the present study. Work efficiency was deduced from the $\dot{V}O_2$ measurements. For the non-pregnant level they measured $\dot{V}O_2$ at 6 months after delivery. They found no reduction in work efficiency during pregnancy, only in the puerperium. In this athlete work efficiency was improved at moderate work. Thus at 36 weeks gestation an additional 345 ml of oxygen were needed during a workload of 40 W, and 470 ml of oxygen when the workload was 70 W.

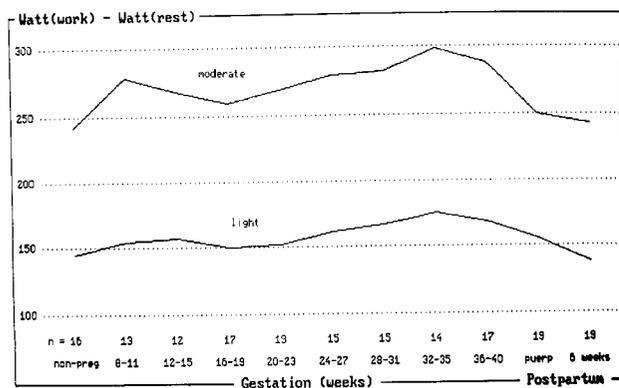


Fig. 15.1. Median increase in physiological workload during light and moderate work compared with resting levels.

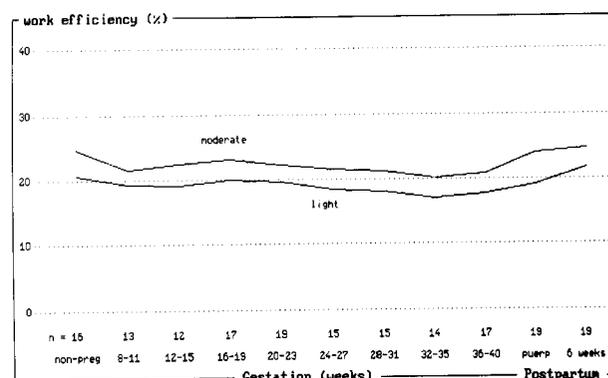


Fig. 15.2. Median work efficiency during light and moderate work.

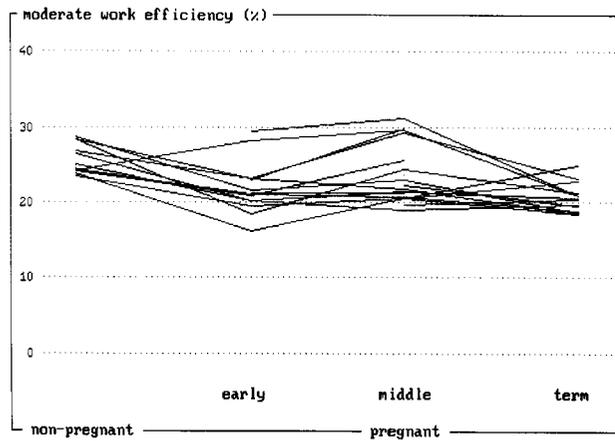


Fig. 15.3. Individual work efficiency during moderate work.

Clapp (1989) studied 18 fit recreational athletes during treadmill exercise. He found that in early pregnancy efficiency was improved in all of them. Nine women discontinued their regular exercise and then showed a progressive decline in their work efficiency, whereas those who maintained their exercise

Table 4. Trends of change during moderate work*

Variable	Trend*	P (Wilcoxon)	Gestation (weeks)
$\dot{V}O_2$	+	0.003	8-11
$\dot{V}CO_2$	+	0.003	8-11
V	+	0.006	8-11
f_R	-	0.096	20-23
\dot{V}_T	+	0.036	8-11
\dot{V}_A	+	0.005	8-11
$PAco_2$	+	0.003	20-23
f_C	+	0.056	8-11
$\dot{V}O_2/f_C$	+	0.051	8-11
Work efficiency	-	0.013	8-11

*(+) indicates increase, (-) indicates decrease.

For abbreviations see Abbreviation section on p. iv.

retained their work efficiency.

Table 4 summarizes the trend of the changes and the statistical differences of the various variables during moderate work comparing the women before and during pregnancy. It also indicates when these changes became significant.

16. General discussion of the cardiopulmonary adaptation to exercise

During pregnancy a woman needs calories over and above her basal requirements for changes in her own body and for the growth of her fetus. From the point of view of measurement, O_2 is best suited for calculating such requirements.

As has been described in Chapters 3–7, by 8–11 weeks gestation there were already marked changes in most of the cardiopulmonary variables studied at rest. Furthermore, as discussed in Chapter 8, these changes were already present when the pregnant women performed their first tests. The increased oxygen demanded by pregnancy was achieved by an increase in \dot{V} . This increase in \dot{V} at rest was caused only by an increase in tidal volume. There was also an improvement in ventilation demonstrated by a fall in the oxygen and carbon dioxide ventilation equivalents. The distribution to the tissues was effected by an increase in \dot{Q} . The latter was the result of an increase in heart rate with a zenith at 32–35 weeks gestation and an increase in stroke volume which remained at the same level during pregnancy from 8–11 weeks gestation.

During exercise additional energy requirements have to be met. We have described the additional effect of work against the background of the changes observed at rest. Thus the effect of a workload is easier to identify and quantify than when the absolute numbers are given.

During bicycle exercise with the women sitting upright more oxygen was needed both for light and for moderate work during pregnancy than in the non-pregnant state, and by 6–8 weeks after delivery the values had not yet returned to basal levels. There was a tendency for the additional oxygen requirements to peak in early pregnancy and again in late pregnancy.

To absorb extra oxygen, \dot{V} increased more and ventilation improved more than during rest. The changes were seen most distinctly in alveolar ventilation which increased in all women during work and in all of them by 8–11 weeks gestation. Somewhat surprisingly, at light work \dot{V} remained the same in non-pregnant as in pregnant women until mid-pregnancy. Also, in contrast to measurements at rest, respiratory rate increased both in the non-pregnant and even more in the pregnant women, particularly from mid-pregnancy until delivery. Tidal volume showed peak values early in pregnancy.

To provide the tissues with the additional oxygen needed, cardiac output must increase. Non-invasive methods for estimating \dot{Q} during work are unreliable. However, the amount of oxygen delivered for each heart beat, i.e. the oxygen pulse being a function of stroke volume and the A–V difference for oxygen, gives at least an idea of the direction of the changes. Estimated stroke volume increased more during work when the women were pregnant than in the non-pregnant state, and was highest in early and late pregnancy. Heart rate increased during work, but particularly during moderate work in late pregnancy heart rate increased less than when the women were not pregnant.

Thus cardiac output must also have been less, which agrees

with the observation that six of the women felt from mid-pregnancy that a workload of 60 W was too much and the load was reduced to 50 W. On the other hand, we found that oxygen consumption was at a peak level in late pregnancy and during moderate work. Thus, the crucial oxygen was absorbed and must have been distributed to the tissues. This reduced heart rate reaction during work in the last months of pregnancy is the only finding in the present study that might indicate a limitation of the fetal oxygen supply. We do not know the mechanism behind this. Future studies are needed to see if there is any relation between this lack of increase in maternal heart rate during exercise and the 30% increase of impedance and the 2–25% decrease in flow in the uterine circulation during sub-maximal exercise (Erkkola *et al.* 1992). Could it be that because of the oxygen demands from the maternal muscles, the visceral, including the uterine, circulation is so reduced that heart rate can be less increased because the shunt type of circulation to the placental site is partially shut down? The individual curves in Fig. 14.4 show that such was not always the case. This is one of the several occasions in this study where it is tempting to make a general statement from the median curves, only to find that in the individual case the situation may be different.

In the puerperium the changes seen during light and moderate work compared with the resting levels were consistently between the levels at term and those in the non-pregnant state, the heart rate being the exception. The relatively small rise in heart rate just described in late pregnancy is in contrast to the Δf_c in the puerperium which was as high as in the peak periods during pregnancy. Consequently the oxygen pulse increase was also at a nadir in the puerperium.

Work efficiency during light and moderate work was consistently lower in the pregnant women than when they were not pregnant; moreover, work efficiency fell gradually towards term. The work efficiency increased from 20% during light work to 25% during moderate work, thereby facilitating the latter.

In addition to the textbooks and review cited above, there are the recent short reviews on pregnancy and exercise, undoubtedly called for because of the marked increase in general interest in sports and exercise, by Clapp (1990) and by Huch & Erkkola (1990). They both stress that as pregnancy itself requires an increased oxygen consumption, the reserves for maximal exercise are reduced.

As different women work in different situations or want to perform different types of exercise, it is an advantage that studies have used varied test protocols, as reviewed by Artal & Wiswell (1986). For example, treadmill exercise, which is weight dependent, differs from bicycle ergometry, which is not. Thus the different results obtained by different authors are partly due to these variations in the methods of study.

Some of the differences in the results from study to study are due to technical variations but, as illustrated here, the individual variability both in the initial level of any of the variables

studied or in their changes in the course of pregnancy, in the puerperium or later, is such that very different results may be obtained when presenting the data.

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