SECTION B

Functional consequences of peripheral airway changes - studies on maximal oxygen uptake.
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INTRODUCTION

The evidence presented in the previous section shows conclusively, the existence of peripheral airway narrowing in young asymptomatic smokers. Narrowed peripheral airways cause inequalities in distribution of ventilation and abnormalities in gas exchange. McFadden and Linden (1972)\textsuperscript{155} demonstrated abnormally high alveolar arterial oxygen gradients in smokers, during rest and exercise. However, these were in older subjects with some respiratory symptoms. Streider and Kazemi (1967)\textsuperscript{213} have reported hypoxemia in young asymptomatic smokers. Krumholz et al. (1964)\textsuperscript{119} demonstrated significantly greater oxygen debt during submaximal exercise in young smokers than in young nonsmokers. Other studies\textsuperscript{119,149,232} have shown a decreased diffusing capacity of oxygen in smokers. Thus, there is a considerable body of evidence pointing to the existence of abnormalities of gas exchange in young asymptomatic smokers.

Normally the alveolar-arterial gradient of oxygen tension increases with increasing levels of exercise,\textsuperscript{28} and in athletes who are well trained, significant arterial desaturation as low as 83% may be observed during exhausting exercise.\textsuperscript{192} This is thought to be due to an increase in the velocity of pulmonary blood flow causing a decrease in the time available for
diffusion of oxygen and the opening up of arteriovenous shunts in the pulmonary circulation. Therefore, in smokers who already have an abnormally high alveolar arterial oxygen gradient at rest and during submaximal exercise, a much greater level of arterial desaturation is likely to occur at maximal work loads, compared to nonsmokers. Thus, the existing peripheral airway narrowing in smokers may well cause a limitation of maximal oxygen uptake. However, Chevalier et al. (1963) studied the cardiopulmonary responses to exercise in young smokers of relatively short smoking histories and nonsmokers of a similar age, and found no significant differences in arterial desaturation, at rest and during exercise. The lack of difference in arterial desaturation between smokers and nonsmokers in their study, may have been due to the fact that these subjects were not sufficiently stressed with maximal loads. Their work test was limited to 5 minutes and the work load was not specified. Therefore, the subjects may not have reached intensities of work loads sufficient to induce significant arterial desaturation.

Though oxygen uptakes at rest and at submaximal exercise have been studied in young smokers, no studies have been performed on maximal oxygen uptakes in such subjects; neither has the effect of small airway narrowing on the maximal oxygen uptake of smokers.
been evaluated.

Maximal oxygen uptake or aerobic capacity is a parameter of great value in the physiologic evaluation of an individual. The ability of the cardiopulmonary systems to deliver oxygen to the tissues is an important factor that determines the ability of an individual to carry on extended work. It is therefore considered to be the best indicator of physical fitness.\textsuperscript{18} Hence, it was decided to measure the maximal oxygen uptake in asymptomatic smokers and nonsmokers and to evaluate it in terms of peripheral airway narrowing.
METHODS

30 volunteers out of the 102 subjects in the cross sectional study and an additional heavy smoker who volunteered were studied. The tests were explained to the subjects and only those who were willing to exercise till exhaustion were included in the study.

None of these subjects had, or was convalescing from any acute illness, nor were they in physical training at the time of the study. All subjects had abstained from smoking for at least two hours before the test, so that any immediate effects of smoking would have disappeared. The tests on all the subjects were performed about two to three hours after a meal. The subject was required to refrain from energetic physical activity for 2 hours preceding the work test.

In all instances test schedules were so arranged, that each subject was tested at the same relative time of the day. Laboratory temperatures ranged from 28°C to 32°C. These were temperatures to which the subjects were well accustomed. Constant circulation of air was maintained in the laboratory with an electric fan. The oxygen content of the ambient air in the laboratory was between 20.87% and 20.94%.

On reporting for the test, each subject had his standing height and weight taken. Height was taken
Experimental set up for the study of physical fitness:

a = Hans stimulus high velocity low resistance valve
b = cycle ergometer
c = muscle ssi

d = oes meter
e = metronome
with the subject bare foot. Haemoglobin was estimated on all the subjects by the cyanmethaemoglobin method using capillary blood obtained from a finger prick.\textsuperscript{56}

Maximal oxygen uptake was measured during bicycle riding on an ergometer with a mechanical braking system. The pedalling rate was kept constant at 60 revolutions per minute (rpm) with the aid of a metronome and the load was increased by increasing the braking resistance on the wheel. Each subject was studied on two different days with an interval of 2-4 days in between. Figure 11 shows the experimental set up for this study.

On the first test day, the procedure used was one of increasing loads with rest periods in between.\textsuperscript{22} The subject was seated comfortably on the bicycle. A nose clip was applied and he breathed through a rubber mouthpiece and a Hans Rudolph high velocity, low resistance valve with a deadspace of 77 ml. The inlet of the valve was open to the atmosphere. The outlet was connected through a T-tap to a Douglas bag. Except during the last minute of each exercise period, when expired air was collected, the outlet of the T-tap was kept open to the atmosphere. Two or three submaximal work loads were used. The starting load was 640 kilopond metres (kpm) per minute (1 kilopond is the force acting on the mass of 1 kg at normal acceleration of gravity; $g = 981 \text{ cm} \cdot \text{sec}^{-2}$).
The subject worked at this load for 5 minutes, and during the last minute of the exercise, heart rate was determined by auscultation and expired air was collected in the Douglas bag. The subject was then allowed to rest for 5 to 10 minutes, after which the load was increased by 320 kpm/min. The procedure was continued in this manner until the subject had reached a work load that he was unable to maintain for at least 3 minutes. At each work load, expired air was collected and heart rate determined during the last minute of exercise.

On the second test day, a continuous series of increasing work loads was used. The subject was started on a work load of 640 kpm/min and this was increased by 320 kpm/min each time. Each load was maintained for 2 minutes. Expired air was collected and heart rate determined during the second minute, at each load. The test was stopped when the subject could not go on any longer. The subject was instructed to indicate by lifting his hand, when he was nearing the point of exhaustion. This enabled collection of expired air and determination of heart rate during the last half to one minute.

The volume of expired air was measured with a dry gas meter, and expired air analyses were performed on a Scholander microgas analyser. The highest value obtained in the two tests was taken as the maximal oxygen uptake for each subject.
<table>
<thead>
<tr>
<th>SUBJECTS</th>
<th>SMOKING CATEGORY</th>
<th>NUMBER OF SUBJECTS</th>
<th>AGE YEARS</th>
<th>HEIGHT cm</th>
<th>WEIGHT kg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>MEAN</td>
<td>± 1 SD</td>
<td>MEAN</td>
</tr>
<tr>
<td>Active</td>
<td>NS</td>
<td>5</td>
<td>20.2</td>
<td>2.28</td>
<td>172.4</td>
</tr>
<tr>
<td></td>
<td>LS</td>
<td>5</td>
<td>19.4</td>
<td>1.73</td>
<td>169.8</td>
</tr>
<tr>
<td></td>
<td>HS</td>
<td>4</td>
<td>20.2</td>
<td>0.96</td>
<td>173.3</td>
</tr>
<tr>
<td>Sedentary</td>
<td>NS</td>
<td>6</td>
<td>21.3</td>
<td>2.16</td>
<td>166.7</td>
</tr>
<tr>
<td></td>
<td>LS</td>
<td>5</td>
<td>19.0</td>
<td>1.87</td>
<td>174.5</td>
</tr>
<tr>
<td></td>
<td>HS</td>
<td>6</td>
<td>20.5</td>
<td>0.34</td>
<td>170.5</td>
</tr>
</tbody>
</table>

NS - Nonsmokers. LS - Light smokers (0-1000 packs)
HS - Heavy smokers (1001 packs and above).

The age, height and weight of the three smoking categories in each group were not significantly different from each other (p > 0.05).
MAXIMAL OXYGEN UPTAKE IN RELATION TO BODY WEIGHT

ACTIVE

\[ y = 0.0283x + 0.728 \]

\[ r = 0.51 \]

SEDENTARY

\[ y = 0.0361x + 0.063 \]

\[ r = 0.84 \]

- Non smokers
- Light smokers
- Heavy smokers

Fig. 12a and 12b

Relationship of \( V_{O_2} \) max to body weight in the active and sedentary groups.
RESULTS

The 31 subjects who participated in the study had varying habits of physical activity and were therefore divided into two groups, active and sedentary. The active group included subjects who took part in some form of active physical exercise regularly and the sedentary group included the rest. There were 14 active subjects and 17 sedentary subjects. Each group was further subdivided into nonsmokers, light smokers and heavy smokers. The active group had 5 nonsmokers, 5 light smokers and 4 heavy smokers and the sedentary group contained 6 nonsmokers, 5 light smokers and 6 heavy smokers.

Table 3 presents the anthropometric data of the subjects, grouped according to smoking habits and activity. There were no significant differences in the age, height and weight among the various categories.

Figures 12a and 12b present the relationship between maximal oxygen uptakes and body weight in the active and sedentary groups. There was a high correlation in both groups (active, \( r = 0.51 \) and sedentary, \( r = 0.64 \)). Therefore, oxygen consumptions were corrected for body weight and expressed as oxygen uptake per kg body weight, STPD.

Table 10 gives the means and standard deviations of the haemoglobin values, maximal oxygen uptakes and
<table>
<thead>
<tr>
<th>SUBJECTS</th>
<th>SMOKING CATEGORY</th>
<th>HAEMOGLOBIN G/100 ml</th>
<th>MAXIMAL OXYGEN UPTAKE STPD L/min</th>
<th>OXYGEN PULSE ml/beat/kg</th>
<th>OXYGEN PULSE ml/beat</th>
<th>OXYGEN PULSE ml/beat/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>MEAN ± 1 SD</td>
<td>MEAN ± 1 SD</td>
<td>MEAN ± 1 SD</td>
<td>MEAN ± 1 SD</td>
<td>MEAN ± 1 SD</td>
</tr>
<tr>
<td>ACTIVE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NS</td>
<td></td>
<td>12.3 ± 1.92</td>
<td>2.53 ± 0.32</td>
<td>45.28 ± 4.58</td>
<td>13.50 ± 1.97</td>
<td>0.242 ± 0.027</td>
</tr>
<tr>
<td>LS</td>
<td></td>
<td>13.1 ± 0.56</td>
<td>2.37 ± 0.63</td>
<td>39.72 ± 5.75</td>
<td>12.96 ± 3.09</td>
<td>0.217 ± 0.021</td>
</tr>
<tr>
<td>HS</td>
<td></td>
<td>12.6 ± 0.92</td>
<td>2.21 ± 0.05</td>
<td>36.93 ± 4.78</td>
<td>11.98 ± 0.65</td>
<td>0.200 ± 0.024</td>
</tr>
<tr>
<td>SEDENTARY</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NS</td>
<td></td>
<td>13.6 ± 0.62</td>
<td>2.05 ± 0.40</td>
<td>38.07 ± 2.23</td>
<td>11.14 ± 2.03</td>
<td>0.207 ± 0.007</td>
</tr>
<tr>
<td>LS</td>
<td></td>
<td>13.6 ± 1.50</td>
<td>2.14 ± 0.06</td>
<td>37.04 ± 1.66</td>
<td>11.76 ± 0.94</td>
<td>0.207 ± 0.021</td>
</tr>
<tr>
<td>HS</td>
<td></td>
<td>13.5 ± 1.13</td>
<td>1.96 ± 0.25</td>
<td>36.52 ± 4.09</td>
<td>10.35 ± 1.21</td>
<td>0.203 ± 0.013</td>
</tr>
</tbody>
</table>

The maximal oxygen uptake and oxygen pulse at maximal oxygen uptake were significantly different (P < 0.05) between the heavy smokers and nonsmokers of the active group. The haemoglobin values of the various smoking categories were not significantly different from each other (P > 0.05).
relationship of oxygen uptake to work load in the active and sedentary groups.
the oxygen pulse (oxygen uptake per heart beat) attained during maximal oxygen uptake, for the different groups. The maximal oxygen uptake when corrected for body weight, showed a significant difference between nonsmokers and heavy smokers, in the active group \((P < 0.05)\) and a slight difference between the two in the sedentary group \((P > 0.05)\). The oxygen pulse which is a measure of the oxygen uptake per heart beat, even when corrected for body size was significantly higher \((P < 0.05)\) in the nonsmokers, than in the heavy smokers of the active group. No differences were observed in the sedentary group.

Figures 13a and 13b show the relationship between the work loads and the oxygen uptakes in the active and sedentary groups. The heavy, light and nonsmokers of the active group attained maximal loads of 1920 kpm/min. In the sedentary group, the nonsmokers attained maximal loads of 1600 kpm/min whereas the light and heavy smokers reached only 1280 kpm/min. In the sedentary group, there were no significant differences \((P > 0.05)\) in the oxygen uptakes of the three smoking categories, at submaximal and maximal work loads. However, in the active group, though there were no significant differences \((P > 0.05)\) in the oxygen uptakes at submaximal work loads among the nonsmokers, light smokers and heavy smokers, at maximal work loads the oxygen uptake of
HEART RATE IN RELATION TO OXYGEN UPTAKE

ACTIVE
- Non smokers
- Light smokers
- Heavy smokers

SEDENTARY
- Non smokers
- Light smokers
- Heavy smokers

Relationship of heart rate to oxygen uptake in the active and sedentary states.
OXYGEN PULSE IN RELATION TO WORK LOAD

ACTIVE
- Non smokers
- Light smokers
- Heavy smokers

SEDENTARY
- Non smokers
- Light smokers
- Heavy smokers

Fig.15a
Relationship of oxygen pulse to work loads in the active and sedentary groups.
the heavy smokers was significantly lower \((P < 0.05)\) than that of the nonsmokers.

Figures 14a and 14b depict the relationship between oxygen uptakes and the heart rates in the different groups. These show that at submaximal oxygen uptakes, in both groups the heavy smokers had the highest and the nonsmokers the lowest heart rates; on the other hand, at maximal oxygen uptakes in the active group, the heart rates of the heavy smokers were lower than those of nonsmokers, and in the sedentary group were similar to those of nonsmokers. It can also be seen that at submaximal and maximal oxygen uptakes, the heart rates of the sedentary group were higher than those of the active group.

Figures 15a and 15b show the oxygen pulse/kg in the various groups, at different work loads. The oxygen pulse/kg of the heavy smokers in the active group was lower than that of the nonsmokers and light smokers. At maximal work loads, this difference was statistically significant \((P < 0.05)\). In the sedentary group, the oxygen pulse/kg was not significantly different \((P > 0.05)\) in the three smoking categories, at submaximal and maximal work loads.

Thus, in the active group, the heavy smokers had significantly lower maximal oxygen uptakes, higher submaximal heart rates, but lower maximal heart rates
TABLE 11

RESPIRATORY QUOTIENTS AT MAXIMAL OXYGEN UPTAKES

<table>
<thead>
<tr>
<th>SUBJECTS</th>
<th>SMOKING CATEGORY</th>
<th>RESPIRATORY QUOTIENT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>MEAN</td>
</tr>
<tr>
<td>Active</td>
<td>NS</td>
<td>1.18</td>
</tr>
<tr>
<td></td>
<td>LS</td>
<td>1.11</td>
</tr>
<tr>
<td></td>
<td>HS</td>
<td>1.13</td>
</tr>
<tr>
<td>Sedentary</td>
<td>NS</td>
<td>1.15</td>
</tr>
<tr>
<td></td>
<td>LS</td>
<td>1.16</td>
</tr>
<tr>
<td></td>
<td>HS</td>
<td>1.13</td>
</tr>
</tbody>
</table>

The values in the different smoking categories were not significantly different from each other ($P > 0.05$).
Relationship of pulmonary ventilation to oxygen uptake in the active group.
Relationship of pulmonary ventilation to oxygen uptake in the sedentary group.
<table>
<thead>
<tr>
<th>SMOKING CATEGORY</th>
<th>FEV(_{1.0}/FVC)%</th>
<th>FEF 30-20%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MEAN</td>
<td>± 1 SD</td>
</tr>
<tr>
<td>Active</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nonsmokers</td>
<td>92</td>
<td>4.64</td>
</tr>
<tr>
<td>Light smokers</td>
<td>90</td>
<td>7.52</td>
</tr>
<tr>
<td>Heavy smokers</td>
<td>88</td>
<td>5.51</td>
</tr>
<tr>
<td>Sedentary</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nonsmokers</td>
<td>90</td>
<td>5.04</td>
</tr>
<tr>
<td>Light smokers</td>
<td>88</td>
<td>3.71</td>
</tr>
<tr>
<td>Heavy smokers</td>
<td>86</td>
<td>9.68</td>
</tr>
</tbody>
</table>

The values were not significantly different from each other in the different smoking categories (\(P > 0.05\)).
and lower oxygen pulse than the nonsmokers. In the sedentary group, the heavy smokers had slightly lower maximal oxygen uptakes, higher submaximal heart rates and similar maximal heart rates and oxygen pulse, when compared to the nonsmokers.

Table 11 presents the mean respiratory quotients of the various groups at maximal oxygen uptakes. No significant difference was observed in these values among the different smoking groups. Figures 16a and 16b depict the individual pulmonary ventilation values in relation to oxygen uptakes in the different smoking categories. There was a wide range in the pulmonary ventilation reached at maximal oxygen uptakes, which is seen clearly in these figures.

Table 12 presents the mean values and standard deviations of FEV$_1$% and FEF 30–20% in the different smoking categories of the active and sedentary groups. This data was available for 30 out of the 31 subjects. These two parameters were chosen, because results obtained from the cross sectional study, described on page 40 indicate that these are the indices that are most sensitive to early small airway changes. In both the sedentary and the active groups, the nonsmokers had the highest and the heavy smokers the lowest FEV$_1$ and FEF 30–20%.

Figures 17a and 17b show the relationship between
MAXIMAL OXYGEN UPTAKE IN RELATION TO FEF 30-20%.

ACTIVE \( r = 0.30 \)
- Non smokers
- Light smokers
- Heavy smokers

\[ y = 2.332x + 34.930 \]

SEDENTARY \( r = 0.29 \)
- Non smokers
- Light smokers
- Heavy smokers

\[ y = 1.024x + 34.699 \]

Figs. 17a and 17b.
"In animals maximal oxygen uptake to FEF 30-20% in the active groups."
maximal oxygen uptake and the FEF 30-20% in the sedentary and active groups. There was a positive correlation between these parameters in both the groups ($r = 0.30$ for the active group and 0.29 for the sedentary group).
DISCUSSION

Oxygen uptakes

All the subjects had worked at submaximal loads of 640 and 960 kpm/min for five minutes and at higher work loads for at least three minutes. These periods are considered sufficient for the attainment of the "steady state". The oxygen uptake increased linearly with increasing work loads (Figures 13a and 13b). At submaximal work loads, there was no significant difference in the oxygen uptake of the different smoking categories, either in the sedentary group or in the active group; neither was there any significant difference in the submaximal oxygen uptakes between the sedentary and active groups. The oxygen cost i.e. \( \frac{\text{oxygen uptake}}{\text{work load}} \) at submaximal work loads is influenced by two factors, the mechanical efficiency and the basal metabolic rate of the subject. Athletes are known to have a greater mechanical efficiency and therefore a lower oxygen cost at submaximal work loads. On the other hand, the basal metabolic rate (BMR) of athletes is 10 - 20% higher than that of sedentary subjects. These two opposing effects probably explain the lack of significant differences in submaximal oxygen uptakes between the sedentary and active subjects.
The maximal \( O_2 \) uptake values for each subject, obtained on the two test days were not significantly different from each other. The mean values were within 1%, indicating that the subjects did reach truly maximal oxygen uptakes during the maximal work loads. The maximal oxygen uptakes obtained for the sedentary subjects in this study were in the range of 29.4 ml/kg to 41.3 ml/kg and were similar to those reported for Asians.\(^7\) Wyndham et al.\(^{1963}\)\(^\text{241} \) reported closely similar maximal uptakes for seven sedentary Caucasian subjects of an older age group. Values for Eskimos,\(^{10,126} \) and the Easter Islanders\(^\text{126} \) have varied from 27 to 47 ml/kg/min for ages ranging from 14 to 45 years.

The values for the active subjects in the present study ranged from 31.3 ml/kg to 49.2 ml/kg. These were similar to the values of active but older Caucasian subjects but were lower than those reported for South African Bantus and the Bushmen of the Kalahari desert,\(^\text{241} \) and much lower than those reported for most white populations of an age group, similar to that of the subjects studied here. This difference could not have been due to a difference in body size, since the maximal oxygen uptakes were expressed as ml per kg body weight. Knutten (1957)\(^\text{116} \) found mean maximal oxygen uptakes of 50.3 ml/min/kg in a group of white American adolescent boys. Åstrand (1964)\(^\text{21} \) reported \( V_{\text{O}_2\text{max}} \) of 50 ml/min/kg
in Swedish male physical education students. Hermansen and Andersen (1965) obtained values of 71 ml/min/kg in a group of world class athletes. One of the reasons for the lower values obtained in the active group of the present study, is that these students although taking part in regular outdoor activity, were not in any way engaged in physical training or in competitive athletics of the endurance type. The difference could also be partly due to ethnic variations in work capacity. On the other hand, Davies et al. (1972) studied 177 men and women of four different ethnic groups, (European, Nigerian, Kurdish and Yemenite Jews) aged 18-30 years and found no significant differences. Yet another factor which may contribute to these differences, is the possible variation in haemoglobin levels. The haemoglobin value of a subject is an important determinant of his $V_{O2}^{\max}$. The mean haemoglobin levels of the present subjects were low when compared to western norms and this may be an important reason for their lower maximal oxygen uptake as compared to their western counterparts. In most of the published studies, the haemoglobin levels of the subjects have not been reported. Lastly, differences in muscle mass in relation to body weight due to variations in dietary and exercise habits, could also be a factor determining differences in $V_{O2}^{\max}$.241
The maximal oxygen uptakes of the active group were higher \((P < 0.05)\) than those of the sedentary group. In each group, the nonsmokers achieved the highest maximal oxygen uptakes and the heavy smokers, the lowest. The difference in these values between the nonsmokers and the heavy smokers was slight in the sedentary group, but marked in the active group. The mean \(V_O^{max/\text{kg}}\) of the active nonsmoker was 45.28 ml/min whereas the \(V_O^{max/\text{kg}}\) of the active heavy smoker was 36.93 ml/min. This difference is not likely to be due to differing levels of physical activity, as great care was taken in the grouping of the subjects according to activity. The smokers and the nonsmokers of the active group in many cases were team-mates in various games. Variations in haemoglobin levels cannot account for this difference, as the mean haemoglobin levels in the two groups were not significantly different \((P > 0.05)\).

Other factors that could temporarily affect the maximal oxygen uptakes are unfavourable environmental conditions, uncomfortable work positions, prior intake of drugs, or tobacco smoking just before the test.\(^{22}\) These factors were excluded from this study by the strict precautions observed.

The difference in maximal oxygen uptakes between the active heavy smokers and nonsmokers is therefore most probably due to the effects of smoking on the
arterial oxygen tensions in the smokers. Though the arterial oxygen tensions or saturations were not measured in this study, there is ample evidence from other published data, that smokers have greater A-aDO₂, \(^{155}\) lower levels of arterial oxygen saturation, \(^{244}\) and lower oxygen diffusing capacity \(^{119,149,232}\) than nonsmokers. Since arterial desaturation is known to increase with increasing levels of exercise \(^{28,192}\) this could be expected to have occurred in both nonsmokers and smokers subjected to increasing work loads in this study. Therefore, as explained earlier in this section (page 66) it is clear that during exercise different degrees of arterial desaturation must have occurred in the various subjects in this study, with the smokers having greater degrees of desaturation than the nonsmokers.

Arterial desaturation is an important factor that influences the oxygen uptake of an individual. The increasing oxygen uptake during increasing work loads is achieved by increasing blood flow to the muscles and by increasing oxygen extraction from the blood in the tissues. Arterial desaturation limits the oxygen uptake by decreasing the oxygen available for extraction. With mild degrees of desaturation, as would be expected to occur in young smokers, this limitation of oxygen uptake would be present only at very high
work loads. Since in the sedentary group, the subjects were unable to reach such high work loads, there was only a slight difference in oxygen uptake between smokers and nonsmokers. However, in the active group the subjects were able to reach very heavy work loads and consequently a significant difference in oxygen uptake was seen between smokers and nonsmokers.

The active nonsmoker by virtue of his physical activity has a higher maximal oxygen uptake than the sedentary non-smoker, but this advantage is nullified in the active smoker, because his impaired gas exchange sets a limit to the maximum oxygen uptake that he can achieve.

**Heart rate and oxygen pulse**

At submaximal work loads, the heart rates of the nonsmokers were lower than those of the smokers, in both the active and the sedentary groups (Figs. 14a and 14b). Also, the heart rates at submaximal work loads of the active group as a whole were lower than those of the sedentary group at similar work loads. A lower submaximal heart rate is an accepted criterion of physical fitness, because a fit person is able to transport the same amount of oxygen at a lower heart rate than an unfit person. 22

The heart rates showed a linear relationship to oxygen uptake at submaximal work loads, but at higher
work loads, the increments in heart rate became progressively less. Such an asymptotic relationship between heart rate and oxygen uptake has been reported by Wyndham et al. (1959). Increases in oxygen uptake occur by an increase in cardiac output and an increase in oxygen extraction from the blood. The increase in cardiac output itself is accomplished by an increase in heart rate and an increase in stroke volume. Astrand et al. (1964) studied men and women of 20 to 31 years of age and found that the stroke volume reached a maximum value at about 40% of the VO2 max. Therefore, an increase in oxygen uptake beyond this level must occur by an increase in heart rate and an increase in oxygen extraction. Consequently, once the heart rate has approached an asymptote, further increases in oxygen uptake must occur mainly by increasing oxygen extraction. Examination of Figures 14a and 14b show that the heart rates at VO2 max in the heavy smokers were slightly lower than or similar to those in nonsmokers. This appears contradictory, since a subject with higher submaximal heart rate, would be expected to have a higher maximal heart rate also. This is clearly not so in the smokers and there appears to be some limitation in the maximum attainable heart rates in them. A similar phenomenon has been reported by several workers at high altitude, and on exposure to hypoxic
air, in normal people. Higher submaximal heart rates and similar or slightly lower maximal heart rates were obtained at high altitudes as compared to the subjects' sea level values. Breathing pure oxygen at sea level pressures in these cases, reduced the submaximal heart rates and increased the maximal heart rates.\textsuperscript{123,185}

\textsuperscript{o} Astrand and \textsuperscript{o} Astrand (1958)\textsuperscript{19} attributed the limitation of maximal heart rates in persons living at high altitudes to a direct effect of prolonged hypoxemia on the pacemaker. Hartley et al. (1974)\textsuperscript{88} have shown that this reduction of maximal heart rate is reversed by atropine and therefore is probably caused by parasympathetic activity. A similar inability of the ageing heart to reach high maximal rates has been reported.\textsuperscript{11,19} \textsuperscript{o} Astrand and \textsuperscript{o} Astrand (1958)\textsuperscript{19} have suggested that this limitation could also be due to the effect of prolonged hypoxemia on the heart. Such a mechanism would explain the limitation of maximal heart rates seen in the heavy smokers in this study. The chronic mild degree of hypoxemia present in heavy smokers, due to inefficient gas exchange, could cause a limitation of their maximal heart rates. Hypoxemia in these subjects could also be due to the higher carboxyhaemoglobin (COHb) levels in their blood. The gas phase of cigarette smoke contains about 4% carbon monoxide\textsuperscript{223} which would increase the levels of COHb.
saturation of cigarette smokers to values of 3 to 10%. Depending on the environment, the normal non-smoker usually has less than 2% COHb saturation whereas smokers of 1 pack or more a day, may have chronically elevated COHb levels of more than 4%. Carbon monoxide in addition to displacing O\textsubscript{2} from oxyhaemoglobin, shifts the oxyhaemoglobin dissociation curve to the left, causing a decrease in the release of oxygen to the tissues.

It has already been mentioned earlier, that the increasing oxygen uptake after the flattening of the heart rate curve is met with normally by an increased extraction of oxygen from the blood. A high degree of arterial desaturation at heavy work loads would limit the oxygen that can be obtained by this means. Figure 14a shows that in the heavy smokers there was very little further increase in oxygen uptake after the flattening of the heart rate curve. It seems likely therefore that they were unable to increase their oxygen extraction as much as the non-smokers. This can be verified from Table 10 which gives the mean oxygen pulse for the different groups, and from Figure 15a which depicts the relationship between oxygen pulse and work load in the active group. It will be seen that the oxygen made available to the tissues per heart beat was lower in the heavy smokers as compared to the
nonsmokers. Correction for body size by expressing the oxygen pulse as ml per kg body weight did not abolish this difference. The reason for the lower oxygen pulse could be a lower stroke volume and/or a lower oxygen extraction in the smoker.

The slope of the oxygen pulse curve at the high work loads is a measure of the increase in oxygen extraction, since stroke volume must already have reached maximal values at 40% of \( V_{O_2}^{\text{max}} \). In this study this level was attained before work loads of 960 kpm/min were reached (Figs. 13a and 13b). It is clear from Figure 15a that not only was the oxygen pulse lower in the smokers but the slope of the curve at the high work loads achieved in the active group was also less in the smokers. This smaller slope, denotes that the increase in oxygen extraction at high work loads was much less in the smoker than in the nonsmoker.

The effects on both oxygen extraction and stroke volume are probably caused by a common factor, arterial hypoxemia. Pugh (1964) and Alexander et al. (1967) studying cardiac output during muscular exercise found that the stroke volume was lower at high altitudes than at sea level, and attributed this difference to hypoxemia causing a depression of myocardial function at high altitudes. Since changes in stroke volume
were not investigated in this study, the possible contribution of this factor to the limitation of maximal oxygen uptake seen in the smoker is not known.

Therefore, both in the smoker and the subject at high altitudes, the same basic defect namely arterial hypoxemia exists, but for very different reasons. One has a low ambient oxygen tension and therefore a low arterial oxygen tension and content, whereas the other has a normal ambient oxygen tension, and yet a low arterial oxygen tension and content, due to impaired gas exchange, the effects of which in the asymptomatic smoker become apparent only during heavy exercise.

Pulmonary ventilation and respiratory quotients

The pulmonary ventilation increased linearly with oxygen uptake at submaximal work loads, but at higher work loads the increments in pulmonary ventilation for unit increase in \( \dot{V}_O^2 \) were somewhat larger. This exercise hyperventilation is due to accumulation of anaerobic metabolites in the blood. There was a wide range in the maximal pulmonary ventilations reached by the subjects, as seen in Figures 16a and 16b. The values obtained were comparable to other published data. There were no significant differences in the respiratory quotients at maximal work loads in the different groups (Table 11).
The ventilatory equivalents (i.e. the ventilation per litre of oxygen consumption) in the present subjects were similar to values obtained in most published reports. Wyndham et al. (1963) obtained ventilatory equivalents of 29.0 L for Bantus, 28.0 L for Bushmen and 32.4 L for Caucasians. Duncan (1972) observed values of about 30.0 L for a small group of sedentary young Asian males. In the present study, the corresponding values were 30.77 L for the sedentary subjects and 30.38 L for the active subjects.

**Relationship of peripheral airway narrowing to the limitation in maximal oxygen uptake**

The subjects who took part in this study with one exception were also participants in the cross sectional study. The findings reported in Section A (page 47) show that significant peripheral airway narrowing was present in the heavy smokers. Moreover, among the subjects who took part in the physical fitness study, all the nonsmokers and light smokers had normal FEF 30–20% whereas 3 of the heavy smokers had FEF 30–20% below the LLN. A study of their maximal oxygen uptakes also showed significantly lower values in the heavy smokers as compared to the nonsmokers.

The mean FEV₁.0% and FEF 30–20% were highest in the nonsmokers and lowest in heavy smokers. The mean
FEF 30–20% values in the active group were 2.96, 2.43 and 2.25 L/sec for the nonsmokers, light smokers and heavy smokers respectively. FEV₁₀% also showed similar trends among the different smoking categories of the two groups. Although the differences in these parameters were not statistically significant ($P > 0.05$) the trend of these values as seen from Table 12, and the positive relationship between FEF 30–20% and $\dot{V}_{O_2}$ max as seen from Figures 17a and 17b suggest that peripheral airway narrowing has an important role to play in the limitation of the maximal oxygen uptakes. However, other factors also probably contribute to bring about the limitation in maximal oxygen uptakes seen in heavy smokers. The high COHb saturation that exists in smokers, by reducing the oxygen content in the blood and by decreasing the release of oxygen from haemoglobin in the tissues, would set a lower ceiling to the oxygen uptakes in smokers.
SUMMARY

Physical fitness was assessed in 31 subjects including 11 nonsmokers, 10 light smokers and 10 heavy smokers, by the determination of maximal oxygen uptakes, while exercising on a bicycle ergometer.

The heavy smokers had significantly lower maximal oxygen uptakes as compared to the nonsmokers.

In the heavy smokers the submaximal heart rates were higher whereas maximal heart rates were lower than those of the nonsmokers.

The oxygen pulse at maximal work loads and the slope of the oxygen pulse curve were significantly lower in the heavy smokers as compared to the nonsmokers.

In the heavy smokers, FEV$_{1.0}$% and FEF 30-20% were lower than in the nonsmokers. There was a positive correlation between FEF 30-20% and the maximal oxygen uptakes.

The probable causes and significance of the lowered maximal oxygen uptakes in the heavy smokers are discussed.