Distribution of lung density after strenuous, prolonged exercise

GÉRARD MANIER, MARTINE DUCLOS, LAURENT ARSAC, JEAN MOINARD, and FRANÇOIS LAURENT. Distribution of lung density after strenuous, prolonged exercise. J. Appl. Physiol. 87(1): 83–89, 1999.—The postexercise alteration in pulmonary gas exchange in highly aerobically trained subjects depends on both the intensity and the duration of exercise (G. Manier, J. Moinard, and H. Storcheff. J. Appl. Physiol. 75: 2580–2585, 1993; G. Manier, J. Moinard, P. Techoueyres, N. Varène, and H. Guénard. Respir. Physiol. 83: 143–154, 1991). In a recent study that used lung computerized tomography (CT), evidence was found for accumulation of water within the lungs after exercise (C. Caillaud, O. Serre-Cousine, F. Anselme, X. Capdevilla, and C. Prefaut. J. Appl. Physiol. 79: 1226–1232, 1995). On representative slices of the lungs, mean lung density increased by 0.046 ± 0.007 g/cm³ (19%, P < 0.001) in athletes after a triathlon. To verify and quantify the mechanism, we determined the change in pulmonary density and mass after strenuous and prolonged exercise using another exercise protocol and methodology for CT scanning. Nine trained runners (age 30–46 yr) volunteered to participate in the study. Each subject ran for 2 h on a treadmill at a rate corresponding to 75% of maximum O₂ consumption. CT measurements were made before and immediately after the exercise test with the subject supine and holding his breath at a point close to functional residual capacity. The lungs were scanned from the apex to the diaphragm and reconstructed in 8-mm-thick slices. Attenuation values of X-rays in each part of the lung were expressed in Hounsfield units (HU), which are related to density (D): D = 1 + HU/1,000. No significant alteration in pulmonary density (0.37 ± 0.04 vs. 0.35 ± 0.03, not significant) was observed after the 2-h run test. Although lung volume slightly increased (change of 166 ± 205 ml, P < 0.05), lung mass remained stable because of a change in density distribution. We failed to detect any changes in postexercise lung mass, suggesting that other mechanisms need to be considered to explain the observed alterations in pulmonary gas exchange after prolonged strenuous exercise.

computed tomography; lung mass; pulmonary edema

SEVERAL AUTHORS HAVE REPORTED an exercise-induced alteration in pulmonary gas exchange in highly trained athletes (2, 9, 22). We have also noted a constant reduction in alveolar-capillary membrane diffusing capacity (Dm) during the recovery phase of a muscular exercise in two types of athletes and situations: 1) in marathon runners (14), a steep decrease in Dm (−29.0 ± 11.3%; P < 0.001) was observed 30 min after a marathon race; 2) in handball players (13), a smaller decrease in Dm (−8.9 ± 8.1%; P < 0.05) was found after a progressive exercise to exhaustion. Interestingly, the postmarathon decrease in Dm was sufficient, even in the presence of an elevation in pulmonary capillary volume (Vc), to induce a decrease in CO lung transfer (DLCO). This decrease in DLCO, which has been reported by others, was not observed in our second study. This discrepancy suggested an influence of exercise duration on the decrease in Dm and thus in DLCO. These gas-exchange alterations were attributed to either functional or structural alterations in the alveolar-capillary membrane (13, 20).

Our results were also consistent with the observed widening in alveolar-arterial O₂ difference lasting for at least 20 min during the recovery phase at the end of a short period of exercise (6). Studies that used the multiple inert-gas elimination technique have pointed to the respective roles of heterogeneity and decrease in pulmonary diffusing capacity in the widening of alveolar-arterial O₂ difference during exercise (6, 25, 26). A limitation in pulmonary diffusion adds to the inequality of distribution induced by exercise, especially when exercise exceeds O₂ consumption (Vo₂ > 3 l/min) (6). These exercise-dependent phenomena have commonly been attributed to an accumulation of interstitial fluid in the lungs during exercise, which would also account for the postexercise alteration in diffusion. Animal studies (23) have indicated that, immediately after heavy exercise, any fluid formed is rapidly pulled out of the fine septal tissues of the lungs into the perivascular and peribronchial lymphatics, which then become distended to form perivascular and peribronchial cuffs. A recent study performed in rowers (7) suggested that reductions in blood volume from the central circulation to the periphery contributed to the reductions in Vc and DLCO.

In this respect, clinical signs of exercise-induced pulmonary edema have been observed in animal models (23, 27), although there have been few descriptions in healthy athletes (12). However, subclinical pulmonary edema, which might account for such alterations, has yet to be observed in standard chest X-ray (3). Computerized tomographic (CT) imaging might, however, detect such a small relative increases in lung water.

Furthermore, along with morphological information, CT can also provide data on tissue density. Regional lung X-ray attenuation is expressed in Hounsfield units (HU) on CT. Because the lung exhibits a wide
range in density from air to blood, CT is a useful noninvasive method for evaluating attenuation (in HU) and density distribution in normal physiological states. Interstitial edema may be observed not only for the increase in measured lung density (MLD) but also for the alteration in lung density distribution. A recent CT study (1) noted an increase in MLD (0.210 ± 0.009 vs. 0.250 ± 0.010 g/cm³, P < 0.001) and mass in eight athletes soon after the completion of a triathlon. However, in this study only a few representative slices of the lungs were examined, which did not enable determination of either MLD or overall mass of the lung.

To find out whether changes in density are due to changes in inflation, perfusion, lung extravascular water redistribution, or all three, the whole lung needs to be examined. The present study was designed to investigate, by using a standardized laboratory exercise protocol, the distribution of density in the overall lung before and after a strenuous and prolonged run test performed by aerobically trained athletes. Whole-lung CT enabled the measurement of lung volume, giving a value for lung mass from the knowledge of lung density.

We failed to observe any increase in MLD or overall lung mass after the run test. Moreover, the continuous distribution of lung density exhibited a shift in the curve toward lower values of density with a simultaneous slight increase in lung volume at the time of the CT measurements.

**MATERIALS AND METHODS**

**Subjects**

Nine male competitors (age 30–46 yr) participated in the study. They trained regularly for 6–8 h every week. They volunteered to take part in the study and gave their informed consent according to the guidelines of the human subject Institutional Review Committee. They had participated in competitive long-distance running for the past 2–20 yr. The subjects' physical characteristics are presented in Table 1. They were nonsmokers, and none of them reported active asthma or the use of any medication, including bronchodilators or vitamins.

**Protocol and Main Experimentation**

Two weeks before the day of main experimentation, the subject reported to the laboratory and was informed of the procedure. Plethysmographic lung function tests were performed on a treadmill before determination of maximum VO₂ (VO₂max). On the day of the main experiments, the subject was asked to report to the laboratory at 8:00 AM after a 36-h period without intense exercise. He was driven to the Department of Radiology where the control preexercise examination was carried out. He was then driven back to the laboratory to perform the prolonged exercise test. The subject was invited to rest for 20 min while a heart rate (HR) monitor (Sport Tester PE 3000, Laboratory Electro O, Kempele, Finland) was fitted to measure and store HR every 15 s throughout the experiment. The running exercise test was performed on a treadmill at a predetermined speed, corresponding to 75% VO₂max determined previously. During the 2 h, the subject was allowed to drink water from time to time. After this period, he was then driven to the CT Department and rested for <30 min after the end of the exercise. A second functional respiratory study was then carried out to detect any alteration in functional residual capacity (FRC).

**Measurements and Calculations: Lung Function Test**

Vital capacity (VC), FRC, total lung capacity (TLC), residual volume, maximal flow rates during expiration, and bronchial resistance during panting were measured or derived in a constant-volume body plethysmograph (SensorMedics 2800, Anaheim, CA) both before and after the exercise test. Normal values for VC and TLC were taken from Quanjer (19) and Knudson et al. (11).

**Determination of VO₂max**

After medical examination, each subject was invited to rest for 20 min while a HR monitor (Sport Tester PE 3000) was fitted to measure and store HR every 5 s throughout the exercise test. The exhaustive exercise test was carried out on a treadmill for determination of VO₂max. The initial running velocity was 10 km/h after a 10-min warming-up period (running at 8 km/h). Velocity was then increased by 2 km/h every 2 min until 14 km/h and then by 1 km/h every 2 min until the subject could no longer maintain the imposed treadmill velocity. Total exercise duration was 30–32 min. During exercise, the subject breathed through a mouthpiece and a low-resistance, two-way valve (model 2700, Hans Rudolph) into an online computerized breath-by-breath system equipped with a linearized calibrated pneumotachograph (model 3813, Hans Rudolph) and calibrated O₂ and CO₂ analyzers (Desktop, Medical Graphics, St. Paul, MN).

**Table 1. Biometric and spirometric characteristics, years in competition, and VO₂max for each subject**

<table>
<thead>
<tr>
<th>Subject No.</th>
<th>Age, yr</th>
<th>Height, cm</th>
<th>Body Mass, kg</th>
<th>Time in Competition, yr</th>
<th>TLC, liters</th>
<th>VC, liters</th>
<th>FRC, liters</th>
<th>VO₂max, ml·min⁻¹·kg⁻¹</th>
<th>HR, beats/min</th>
<th>Treadmill Rate, km/h</th>
<th>Time on Marathon, h:minMax Before After</th>
<th>Mean ± SD</th>
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<td>73</td>
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</table>

VO₂max, maximal O₂ consumption; TLC, total lung capacity; VC, vital capacity; FRC, functional residual capacity; HR, heart rate; max, maximum; before and after, before and after exercise test.
CT: Lung Volume and MLD

The CT examinations were carried out by using a scanner (Siemens CT Somatom DRH) on 8-mm-thick slices with 1 × 1-mm reconstruction. Acquisition of one slice took 5 s. Slices were taken from the right and left lung, with the subject holding his breath at FRC. Subjects were scanned in the supine position before and after exercise. Acquisition was performed with a 350-mm field of view and a 512 × 512 matrix (pixel size = 350/512 = 0.68 mm). The lungs were scanned from the apex to the diaphragm by using 8-mm-thick slices with no gaps. Attenuation values were expressed in HU. These units are related to density (D) by the expression D = 1 + (HU/1,000), and, by convention, water has a HU value of 0 and air a value of –1,000. The density of a tissue less dense than water thus has a negative HU value. An average of 25 slices was required to cover both lungs. Images were photographed on hard copies by using a window width of 1,200 HU and a window level of –600 HU.

Our image-processing procedure has been widely used for measuring lung density and volume. It is based on an algorithm that accurately delineates lung contour along the parietal and pleural surface from the clear-cut difference between lung density (–700 HU) and pleural mediastinal wall density (60 HU). This algorithm, excluding operator-related reproducibility errors, has been shown to be reliable (10). It includes all the pixels of the image, which reflects lung voxels including medium and small vessels and bronchi. Only hilar structures were excluded by the method. This algorithm ensures that the same region of interest (ROI) is examined on the pre- and postexercise images.

Data were also analyzed by a computer with purpose-designed software that carried out the following operations for left and right lungs. 1) It automatically rejected extrapulmonary tissues by excluding all pixels outside the range –990 to –350 HU. The main pulmonary arteries were also excluded. 2) It calculated the frequency distribution of HU in each slice and in both left and right lungs. 3) It calculated volume (V) and mean HU (as HU mean) within each slice (i). 4) It derived both left (V Ll) and right lung volume (V Lr). 5) It calculated a mean value of HU for both left (HU meanL) and right lungs (HU meanR), and overall lung (HU mean), where HU is the volume-weighted average of all HU values, with HU mean = HU * (V/V Ll/r), where n is the number of slices, V i and HU i are values in the exponent slice, V Ll/r is the left or right lung volume, and V i is the overall lung volume. Derived data were also calculated. Mean MLD is D mean = 1 + (HU mean/1,000). Lung mass (m) is the product D mean * V Ll/r. Total lung mass was the sum of the left and right lung masses. This technique of lung mass calculation has been previously validated by comparing the masses of animal lungs or lobes measured gravimetrically with that determined by the CT method by using the same equipment. The CT method provided the required accuracy and sensitivity (4, 5).

In a final step, the weighted frequency distribution of HU of left and right lung volumes was also calculated for the whole lung. Assuming that the HU value refers to the unit of lung volume, HU frequency corresponds to a percentage of lung volume. Lung volume percentage (Y) was plotted against HU value (X). These HU values were cumulated over an interval of 20 HU values represented by their midvalue along the HU scale from –990 to –350 HU (corresponding to density values ranged from 0.110 to 0.670). For each interval of a HU midvalue, the means ± SD for both volume percent and absolute value of lung volume were calculated for the nine athletes both before and after the exercise test. They were represented graphically both before and after exercise (Fig. 1) to show the distribution of density in the lungs, which may be due to alterations in lung volume, vascular state, or extracellular fluid distribution.

Comparison and Statistical Analysis

CT scans were compared both qualitatively and quantitatively before and after exercise in each subject. Images were compared in a blinded fashion by two independent operators inspecting for areas of ground-glass opacities, condensation, and signs of an increase in pulmonary blood flow parenchymal vessels by counting arteries and veins from the fourth to the sixth orders.

Post- and preexercise values of lung volume, HU mean, MLD, mass, and V Ll/r were compared by using Student’s t-test for paired samples. All results are expressed as means ± SD. Finally, for each interval of a HU midvalue along the HU scale, post- and preexercise values of lung volume were compared by using Student’s t-test for paired samples. The significant baseline value for the probability (P) was chosen at 0.05. The shape of density distributions in the lungs (Fig. 1) was also described both before and after exercise by their four moments, i.e., mean, SD, skewness, and kurtosis.

RESULTS

The biometric and spirometric individual data listed in Table 1 are in the normal range. The mean value of V O2max was 66.4 ± 4.7 ml O2·min⁻¹·kg⁻¹, and the corresponding value of running velocity was 19.5 ± 1.4 km/h. Maximal HR was 187 ± 9 beats/min. The treadmill velocity adjusted for each athlete at 75% of his own V O2max corresponded in the population to a mean value of 14.8 ± 1.2 km/h. All athletes performed the 2-h tests without exhibiting medical symptoms. HR had not completely returned to preexercise control values (58 ± 5 and 81 ± 8 beats/min, before and after exercise, respectively) when the CT examinations were carried out.

![Fig. 1. Lung volume distribution as a function of density before and after exercise.](http://jap.physiology.org/Downloaded from)
Plethysmography

VC, TLC, and FRC were not altered significantly after the exercise test. Preexercise values are presented in Table 1.

Imaging

On preexercise CT, we found no radiological abnormalities justifying exclusion of any of the subjects. Despite the short delay after the exercise test, CT examination did not evidence any areas of ground glass, condensation, or air-space filling. We did not see any clear-cut images of acute interstitial or alveolar pulmonary edema nor any linear opacities or increase in the number of total veins and venules.

CT

Lung volumes, MLD, and lung mass. Densities were of the same order as those reported in the literature when measured at FRC (5, 17). At the time of breathing interruption, the mean whole lung volume determined by CT was slightly higher after than before the exercise test (change = 166 ± 205 ml; P < 0.05; Table 2). Plethysmographic measurements, which were performed after a mean delay of 30 min after CT, failed to show this increase (<5%); this was attributed to the difference in subject's position (supine for CT and upright for plethysmography). CT MLD derived from HU\textsubscript{mean} values remained stable after exercise in both left and right lungs. Only results in the whole lung are presented in Table 2. Lung mass remained constant.

Distribution of lung volume as a function of lung density. Over the range of densities between 0.110 and 0.670 (an interval of expected values of density in the lung parenchyma), the plot of lung volume distribution as a function of density (Fig. 1) was significantly shifted toward lower values of density with a decrease of the first moment of the distribution from 0.299 to 0.281 without a change in SD. Moreover, the shape of these abnormal distributions changed after exercise: skewness increased from 1.095 to 1.217 and kurtosis increased from 0.675 to 0.942.

DISCUSSION

The main result of this study is the absence of a significant change in either MLD or mass, despite an increase in lung volume at the time of postexercise measurement in our population of athletes. A shift in the distribution of lung volume toward lung areas of lower density was observed.

Methodological Aspects

Exercise protocol. Both duration and relative power rate of running for each athlete were standardized in our treadmill exercise protocol. Although lung diffusing capacity was not measured after exercise, 2 h of running at 75% of individual maximal power rate were thought to be sufficient to induce a functional change in pulmonary gas exchange. It should be kept in mind that, in our runners, a 75% VO\textsubscript{2max} run test corresponded effectively to a mean VO\textsubscript{2} (3.6 ± 0.6 l/min) over the 2 h, which is well above the threshold value of 3 l/min of VO\textsubscript{2}. An alteration in diffusion is known to occur below this value even with runs of <2 h (6). Our previous studies and those of other authors have evidenced a constant alteration in either DL\textsubscript{CO} or Dm, pointing to an alteration in the alveolar-capillary membrane in similar postexercise conditions (13–15). However, 2 h of treadmill exercise at 75% VO\textsubscript{2max} is certainly a smaller workload than that of a triathlon performed for the same period of time (1).

Interval between exercise and measurement. The interval between the end of the running period and the start of CT examination was kept to a minimum (<30 min). In the study of Caillaud et al. (1), the postexercise CT examination was carried out after a triathlon competition, and, although the delay was greater than in our study, an increase in CT lung density was noted, which was indicative of postexercise interstitial edema.

CT scanning technique. In the present study, lung density was measured and mass calculated with a methodology that differs somewhat from that used by Caillaud et al. (1). First, hilar and perihilar lung regions were excluded from the ROI by the software

<table>
<thead>
<tr>
<th>Subject No.</th>
<th>Lung Volume, ml</th>
<th>HU\textsubscript{mean}</th>
<th>MLD</th>
<th>Mass, g</th>
</tr>
</thead>
<tbody>
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<td></td>
<td>Before</td>
<td>After</td>
<td>Before</td>
<td>After</td>
</tr>
<tr>
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<td>4,329</td>
<td>4,624</td>
<td>–676</td>
<td>–692</td>
</tr>
</tbody>
</table>

Mean ± SD: 3,722 ± 647, 3,888 ± 631, 0.373 ± 0.044, 0.352 ± 0.027, 1,372.2 ± 178.1, 1,356.4 ± 130.5

Differences: P < 0.05, NS

<table>
<thead>
<tr>
<th>Subject No.</th>
<th>Mean ± SD</th>
<th>Differences</th>
<th>NS</th>
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<tr>
<td>1</td>
<td>166 ± 205</td>
<td>P &lt; 0.05</td>
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</table>

HU\textsubscript{mean}, mean Hounsfield unit of whole lung; MLD, measured lung density; mass, lung mass; before and after, before and after exercise test; NS, not significant.
and not manually (see MATERIALS AND METHODS). Thus voxels in our study were included or excluded solely on the basis of their densities, and the chosen limits of the densities were designed to exclude central great vessels and not small vessels. However, it could be argued that, from a theoretical point of view, our image processing approach could ignore normal preexercise voxels that became edematous after exercise. In fact, the software we used did not permit a comparison between ROIs identical for both pre- and postexercise measurements. Nevertheless, the fact that subjects had both a larger lung volume and a stable MLD postexercise allows us to consider that edematous parenchyma was not systematically excluded from the second image. Second, the whole lung was radiologically reconstructed from 20 to 25 slices 8 mm thick rather than being extrapolated from a few representative lung slices. In the event of slight alterations in the position of each slice after exercise, this type of experimental error would be reduced by our method of taking continuous 8-mm slices rather than a few selected ones. Moreover, postexercise inhomogeneity in lung distribution would be lessened, giving a better estimate of lung density.

Third, the pixel in our study was a volume of approximately 0.3 \( \times \) 0.3 \( \times \) 8 mm\(^3\), and it included small vessels and those of \( \sim 5 \) mm, which were not included in the study of Caillaud et al., where voxels were 0.3 \( \times \) 0.3 \( \times \) 1 mm\(^3\). Visual inspection of the images confirmed that vessels of \( \sim 5 \) mm were included in the calculation of lung density. Although a resolution of 1-mm-thick slices is commonly used for imaging lung structure, we employed a method for determining a continuous distribution of HU with a radiological measurement of lung volume, which gave a more accurate estimate of total lung mass. We felt that this method would give a better evaluation of any interstitial edema, but it could explain the discrepancies between our results (reflecting what happens in the whole lung) and those of Caillaud et al. (reflecting what happens in the peripheral part of the lungs). In these lungs, assuming a 6-liter TLC, there would be a 240-g weight gain if the 0.04 g/cm\(^3\) change in density were constant throughout the lung. Thus because we showed that there was no change in overall lung mass, if there were subtle peripheral edema, a compensatory decrease in intravascular volume should occur to keep the lung mass unchanged. It has been effectively shown (7) that reductions in blood volume from the central circulation to the periphery can occur during and after exercise, and it is not quite excluded that this phenomenon could have minimized the variations of postexercise values of pulmonary densities.

Visual analysis. On the postexercise CT, no pathological radiological signs were found. Hydrostatic interstitial edema is normally accompanied by a 20–30% increase in pulmonary veins and arteries, with a tendency to lung cephalization of the vascular recruitment. We failed to observe any increase in gravitational-dependent opacities, size of pulmonary artery and veins, or any polygonal and/or linear opacities. Despite this normal appearance, the expected increase in extravascular lung water induced by prolonged and strenuous exercise might have been below the resolution of CT.

Lung volume, density, and mass measured at FRC. In our study, the CT measurements were performed at physiological lung volume, i.e., the FRC observed at the time of the exercise protocol. The total lung volume measured with CT (\( V_{\text{L/R}} \)) is the sum of tissue volume (\( V_{\text{t}} \)) and gas volume. Pulmonary density depends on both the relative volume of air and the pulmonary tissue volume (parenchyma, interstitial fluid, blood). If acquisitions are made at FRC, then \( V_{\text{L/R}} = V_{\text{t}} + FRC \).

Guénard et al. (5) have shown that, for a given individual, \( HU_{\text{mean}} \) (and thus MLD) is a hyperbolic function of pulmonary inflation. It has also been demonstrated in animals that inflated and deflated lungs have identical lung mass. Moreover, our values of lung mass were very close to the value obtained by weighing. Thus the CT method that used overall reconstruction can be considered to be a reliable method for determining lung mass. Moreover, if changes in lung mass are accompanied by slight changes in lung volume, they would be assumed to be due solely to alterations in intravascular or extravascular fluid. In our study, values of \( HU_{\text{mean}} \) and MLD are lower and higher, respectively, than those reported by Caillaud et al. (1). This discrepancy probably derives from differences in lung volume at which measurements were performed: FRC in our study and TLC in that of Caillaud et al. Before exercise, the mean CT lung volume was 3.72 ± 0.65 liters, and MLD values were in the normal range at FRC (8). After exercise, CT lung volume rose slightly (0.17 ± 0.21 liter, \( P < 0.05 \)) with no significant change in MLD. The fact that calculated mean lung mass did not change after exercise pointed to a postexercise modification of the distribution of ventilation and density in the lungs. This was supported by the plot of lung volume as a function of lung density (Fig. 1). After exercise, there was a shift in lung volume toward a lower density, which can account for the stability in lung mass despite the increase in overall lung volume at constant MLD.

These results do not agree with those of Caillaud et al. (1), who reported a 19% increase in both MLD and mass in a few 1-mm-thick slices of the lungs of athletes after a triathlon. Although the physiological stress of a competition is likely to be greater than that from a laboratory-controlled treadmill exercise, these differences may also stem from differences in the CT techniques used. First, in the study by Caillaud et al., as the measurements were made at TLC, a negative intrathoracic pressure induced by a deep inspiration might have increased lung blood volume, especially in supine subjects. This could have led to an alteration in lung blood distribution during the exercise recovery period and could have affected the postexercise interpretation of the CT results. Second, a few 1-mm-thick lung slices may not be representative of the whole lung or the postexercise alterations in distribution of lung water and blood flow. In fact, Caillaud et al. reported that parenchymal density increased in each of the six scanned levels in all athletes. It should be noted that their CT measurements used a fixed slice thickness (\( t = \)
1 mm) and that the slice area (a) did not change after the triathlon. It can, therefore, be assumed that the slice volume, the product \( t \times a \), was also constant. This CT slice volume is the sum of the gas of the slice and tissue volume (depending on water accumulation). If MLD and mass increased in the slice with no concomitant change in the CT lung slice, the volume of gas in the slice should have decreased. Their measurements were made at a constant level of TLC, and, for these reasons, the overall lung volume should have increased in the presence of an increase in MLD as a direct effect of the suspected increase in lung water. Caillaud et al. could not determine overall lung volume and hence could not reasonably claim that an increase in mass at the six levels of measurements was representative of a process occurring in the whole lung.

Notwithstanding these comments, our results demonstrate that a 2-h 75% \( \text{VO}_{2\text{max}} \) run test had no significant influence on either MLD or lung mass. In fact, the data presented in Fig. 1 are consistent with a redistribution of tissue, blood, and lymph volume during and after exercise (7, 23), i.e., consistent with the possibility that microvascular blood volume in the fine septal tissue of the alveolar regions had decreased. On the other hand, perivascular and peribronchial tissue volume may have increased by lymphatic engorgement, leaving average lung density unchanged but causing the lung volume to be shifted to less dense regions.

The hypothesis of a water redistribution is reinforced by the postexercise change in the descriptive statistics for lung density distribution (see RESULTS and Fig. 1): first moment decreased and the shape was altered with a postexercise reorganization of lung density as a consequence of a postexercise change in lung water gradient from apex to base. Although there was a higher degree of kurtosis, it is not possible to state whether the lower lobes might have a modest increase in the number of denser voxels. Measurements of tissue volume combined with separate CT of both lung base and lung apex would have been needed to confirm this hypothesis (24).

**Gas Exchange Alteration After Strenuous and Prolonged Exercise**

Our results are consistent with our previous studies on alveolar-capillary Dm in athletes after exercise. By simultaneous measurement of \( \text{DL}_{\text{CO}} \) and NO diffusing capacity, we were able to dissociate the two factors affecting lung diffusing capacity (i.e., Dm and Vc). A significant decrease in Dm was observed in each subject with a maximum of 30% after a marathon run. The alteration in functional diffusion was attributed to structural changes in the alveolar-capillary membrane. Although pulmonary diffusing capacity has not been measured directly in animal models, structural lesions of the membrane have been evidenced in several studies (18, 23).

Electron microscopic examination of slices of lungs after exercise evidenced an alteration in the alveolar-capillary membrane, with rupture of intracellular bridges, and transfer of globules and plasma into the alveolar space (18, 28). However, there are considerable interspecies differences, and dogs in particular are known to be sensitive to respiratory effects of exercise. Although a neurogenic explanation of these alterations has been proposed (16), a hemodynamic account for the postexercise changes in Dm in humans appears the most plausible at present. Nevertheless, there is as yet no direct anatomic evidence in humans.

During intensive exercise, pressure changes in the human pulmonary circulation are of the same order as those observed in animals (21). In animals, measurements indicate membrane alterations at >40-mmHg pulmonary wedge pressure. Membrane damage could be facilitated by alterations in the properties of surface liquid, as the hyperventilation induced by strenuous exercise could have an influence on alveolar surfactants. Our results are not in favor of any significant extravascular accumulation of water in the lungs. Structural modifications of the alveolar-capillary membrane were attributed to mechanisms other than alterations in surfactant or disruption of the membrane itself.

In summary, we failed to detect any increase in pulmonary mass in athletes after a 75% \( \text{VO}_{2\text{max}} \) 2-h run test, despite an increase in lung volume at constant MLD. This was explained by the observed shift in the lung volume distribution toward regions of lower density. Thus our results do not support a significant increase in overall extravascular lung water after strenuous exercise in the present experimental conditions, but they are consistent with an exercise-induced redistribution of lung fluid and blood. Further studies that use a combination of inert gas and CT on whole lung are required to separate the components of lung volume to establish whether pulmonary edema occurs in elite athletes above a threshold exertion during prolonged exercise.

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