Distribution of lung density after strenuous, prolonged exercise

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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 0.040 ± 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.

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

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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 detected 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 and 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).

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<th>Subject No.</th>
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<th>Body Mass, kg</th>
<th>Time in Competition, yr</th>
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<th>VC, liters</th>
<th>VO₂max, ml·min⁻¹·kg⁻¹</th>
<th>HR, beats/min</th>
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Mean ± SD 34.8 ± 6.6 175.2 ± 7.6 70.1 ± 7.1 6.8 ± 2.7 7.1 ± 0.5 5.9 ± 0.5 3.5 ± 0.2 66.4 ± 4.7 187.2 ± 8.8 58.2 ± 5.0 81.4 ± 8.3 14.8 ± 1.2 2.53 ± 0.13

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.

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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 
\[ D = 1 + \left( \frac{HU}{1000} \right), \]
and, by convention, water has a HU value of 0 and air a value of −1000. 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_i) and mean HU (as HU_i) 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 (HUmean_l) and right lungs (HUmean_r), and overall lung (HUmean). Where HU is the volume-weighted average of all HU values, with
\[ HU_{mean} = HU_i \times \left( \frac{V_i}{V_{Ll/r}} \right), \]
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
\[ D_{mean} = 1 + \left( \frac{HU_{mean}}{1000} \right). \]
Lung mass (m) is the product Dm × 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. 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, HUmean, 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.](https://i.imgur.com/3.png)
Plethysmography

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

Scan 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 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% $V_{O2max}$ run test corresponded effectively to a mean $V_{O2}$ (3.6 ± 0.6 l/min) over the 2 h, which is well above the threshold value of 3 l/min of O$_2$. 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 $D_{LCO}$ 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% $V_{O2max}$ 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

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<th>Table 2. Computed tomography-derived data</th>
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<td><strong>Mean ± SD</strong></td>
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$\text{HU mean}$, 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 reduced by our method of taking continuous 8-mm slices rather than being extrapolated from a few representative lung slices. In the event of 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 HUmean 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% \( VO_{2 max} \) 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 maximum of 30% after a marathon run. The hypothesis of a water redistribution is reinforced by the postexercise change in lung density distribution (see RESULTS and Fig. 1): first moment decreased and the shape was altered with a maximum of 30% after a marathon run.

In summary, we failed to detect any increase in pulmonary mass in athletes after a 75% \( VO_{2 max} \) 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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