Estimation of Pulmonary Water Distribution and Pulmonary Congestion by Computed Tomography

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SUMMARY

Computed tomography (CT) of the lung in normal subjects and patients with congestive heart failure was performed in the supine position with deep inspiration to obtain pulmonary CT values and images. The mean CT value in normal subjects was higher in the posterior than anterior lung field, presumably because blood vessels were more dilated in the former than the latter due to the effects of gravity. The mean pulmonary CT value in patients with congestive heart failure was significantly increased possibly due to an increase in blood flow per unit lung volume arising from either pulmonary congestion or pulmonary interstitial and alveolar edema.

The mean pulmonary CT value increased parallel to the severity of pulmonary congestion, interstitial or alveolar edema and was well correlated with the pulmonary arterial wedge pressure, indicating that such a correlation was a valuable tool in assessing therapeutic effects.

The results of the present study indicate that pulmonary CT is useful for the noninvasive estimation of intrapulmonary water content and its distribution, thereby providing an effective diagnostic clue to various conditions in congestive heart failure.

Additional Indexing Words:

Congestive heart failure   Pulmonary CT value   Pulmonary CT image   Pulmonary edema

ROUTINE chest roentgenography plays an important role in the diagnosis of congestive heart failure, providing excellent qualitative but minimal quantitative evidence of pulmonary congestion. Computed tomography (CT) can be used to quantitatively estimate the water content of lung tissue based on the X-ray attenuation coefficient (CT value) per unit vol-

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ume,[1)-4)] thereby providing data on pulmonary water distribution and the severity of congestion in the lung.[5),6)] This study attempted to investigate CT findings in pulmonary congestion in dogs and in patients with congestive heart failure. The relationship with symptomatology, routine chest roentgenography and right heart catheterization was concurrently studied.

I. Experimental study

Methods

Seven adult mongrel dogs weighing 7 to 20 Kg were anesthetized with intravenous pentobarbital sodium (25 mg/Kg) under artificial positive pressure respiration (95% O_2+5% CO_2) with tracheostomy. Epinephrine (0.5 −0.7 mg/Kg) plus normal saline solution (2,500 ml, 38°C) was infused into the femoral vein at various speeds by the methods of Kinoshita et al[7)] and Nakamura et al[8)] in order to produce different grades of acute pulmonary edema. During this procedure, the pulmonary CT value was measured in the supine position as often as needed. In 4 dogs, a Swan-Ganz catheter was inserted through the jugular vein for determination of the right ventricular and pulmonary arterial pressures.

Results

Fig. 1 shows the mean CT value of the right middle lung field in 7 dogs with acute pulmonary edema. The pulmonary CT value started to increase after administering 500 ml of the epinephrine-saline infusion in parallel with the elevation of pulmonary arterial mean pressure. After 1,000–1,500 ml of the infusion, the pulmonary arterial mean pressure increased significantly from 10.3 ± 3.9 mmHg to 26.2 ± 9.0 mmHg ($p<0.005$). The pulmonary

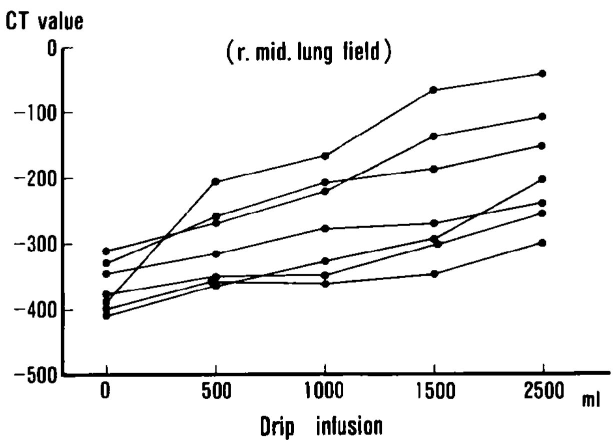

Fig. 1. Mean CT values of the right middle lung field in 7 adult dogs with experimental acute pulmonary edema.

CT images indicated the findings of pulmonary edema in the lower lung field when moist rales were noted at both lower, particularly posterior, lobes. The pulmonary CT value correspondingly increased with the progression of acute pulmonary edema in all dogs. The lung specimens showed marked pulmonary congestion and edema, the severity of which coincided very well with the pulmonary CT findings.

II. Clinical study

Materials and Methods

Twenty-six normal subjects and 45 patients with congestive heart failure of the NYHA functional classification class II or more were studied by pulmonary CT. The patients consisted of 30 persons with valvular heart disease, 6 with acute myocardial infarction, 4 with hypertensive cardiac disease, 3 with congestive cardiomyopathy, and 2 with sick sinus syndrome (Table I).

A low dosage X-ray whole body CT " JEOL dynamic scanner "[9)-13)] was used for the determination of CT value, expressed in 1,000-grade EMI units of " air as −500 ", " water as 0 ", and " bone as +500 ". The range of error was ±0.5%. For comparative analysis of the pulmonary CT value, all studies were done during maximal deep inspiration in the supine position.

Regions of interest (ROI), avoided from large pulmonary vessels, were selected in the peripheral one third of the right and left anterior and posterior lung fields. One ROI consisted of 25 pixels (5×5) with actual dimensions of 14×14×10 mm. Subsequently, the mean CT value of the ROI was calculated by computer and corrected by the CT value of the sponge rubber coating of the examination table (Fig. 2).

A right heart catheterization was performed in 14 patients with mitral valvular disease. In 10 patients with congestive heart failure, the pulmonary

Table I. Patients, Age, and the NYHA Functional Classification

	Number		Age		NYHA		
	M	F	mean	range	II°	III°	IV°
Normal	24	2	35	22-69			
Congestive heart failure							
Mitral valvular disease	8	18	48	26-81	17	7	2
Aortic valvular disease	2	2	51	27-67	2	1	1
Myocardial infarction	3	3	59	34-77	2	1	3
Hypertensive cardiac disease	2	2	60	51-68	1	2	1
Congestive cardiomyopathy	3	0	50	40-66	2	0	1
Sick sinus syndrome	0	2	67	60-73	0	2	0
Total	18	27	52	26-81	24	13	8

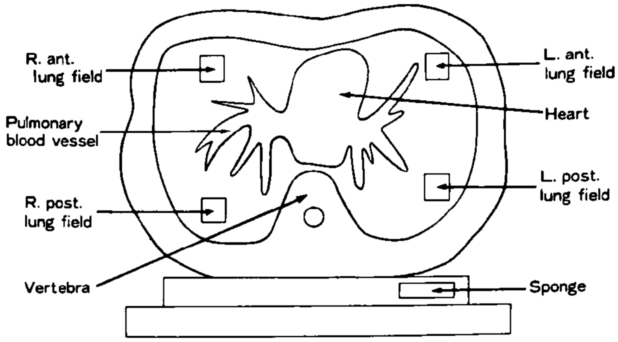

Fig. 2. CT values in four lung fields. Regions of interest (ROI), avoided from large pulmonary vessels, were selected in the peripheral one third of the right and left anterior and posterior lung fields.

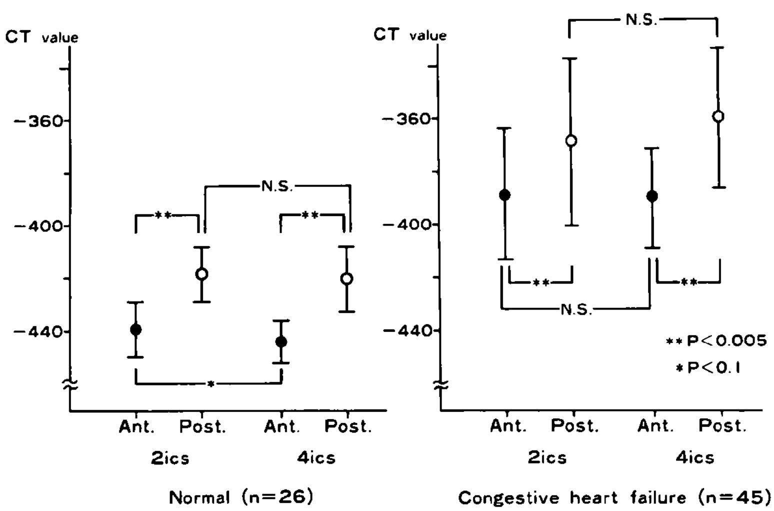

Fig. 3. The pulmonary CT value in normal subjects and in patients with congestive heart failure. In both normal subjects and patients with congestive heart failure, the CT value of the posterior lung field was significantly higher than that of the anterior lung field ($p<0.005$). The CT value in each field was significantly higher ($p<0.005$) in patients with congestive heart failure than in normal subjects.

CT images and hemodynamics were studied before, during, and after administration of digitalis and diuretics.

Results

1) Pulmonary CT values in normal subjects

The CT value was compared in different regions of the lung in the supine position (Fig. 3). In 26 normal subjects, the mean CT value of the anterior and posterior lung fields at the second intercostal space were -439 ± 10.5

(mean±S.D.) and −418.8±10.6, respectively. The mean CT values of the anterior and posterior lung fields at the fourth intercostal space were −444.3±7.4 and −420.5±12.0, respectively. There were no significant differences in the mean CT value between intercostal spaces. However, the mean CT value in the posterior lung field was significantly higher than in the anterior lung field ($p<0.005$) in both the second and fourth intercostal spaces. On the other hand, the value was higher in the anterior than in the posterior lung field in both intercostal spaces in the prone position. In the right decubitus position, the mean CT value was higher in the right anterior and posterior lung fields than in the left ones. The converse was true in the left decubitus position. The CT value was higher during expiration than during inspiration, and higher at the end of systole than at the end of diastole in ECG-gated CT.

2) Pulmonary CT images and values in normal subjects and in patients with congestive heart failure

The CT images of patients with congestive heart failure showed markedly dilated pulmonary vessels radiating from the hilus into the peripheral lung field with a dilated cardiac shadow. Fig. 4 shows the CT images of the chest at the fourth intercostal space in a normal subject and a patient with congestive heart failure of the NYHA functional classification class IV at

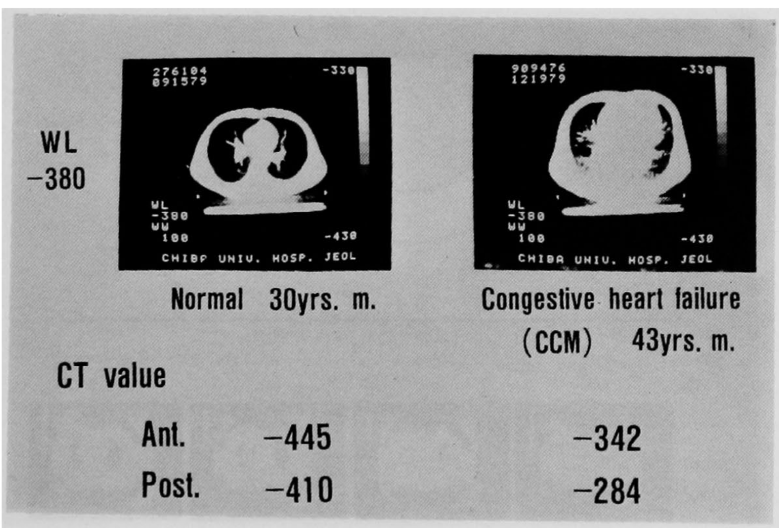

Fig. 4. The pulmonary CT image and CT value at the fourth intercostal space in a normal subject and a patient with congestive heart failure of NYHA functional class IV. The CT image of the patient showed markedly dilated pulmonary vessels radiating from the hilus into the peripheral lung field with a dilated cardiac shadow. Abbreviations: WL=window level; CCM=congestive cardiomyopathy.

a window level of −380 and a window width of 100. The CT values in the anterior and posterior lung fields in Fig. 4 were −342, −284 respectively in the patient with congestive heart failure, and −445, −410 respectively in the normal subject.

The CT values of the anterior and posterior lung fields in the supine position in 45 patients were respectively -388.4 ± 24.9 and -369.0 ± 32.0 at the second intercostal space, and -390.1 ± 18.8 and -360.3 ± 26.9 at the fourth intercostal space. The CT value of the posterior lung field was significantly higher than that of the anterior lung field ($p < 0.005$) for both the second and fourth intercostal spaces. No significant difference in the CT value was noted between intercostal spaces, although the CT value of the posterior lung field at the fourth intercostal space tended to be slightly higher than that of the posterior lung field at the second intercostal space. It was concluded that the CT value was significantly higher in any lung field ($p < 0.005$) in patients with congestive heart failure than in normal subjects (Fig. 3).

3) Case report

F. H. female 51 years: Fig. 5 shows the clinical course and serial CT findings of a patient with hypertensive cardiac disease complicated by acute left ventricular failure. At admission, she was classified as NYHA functional class IV. Chest X-ray revealed marked pulmonary congestion and the Ker-

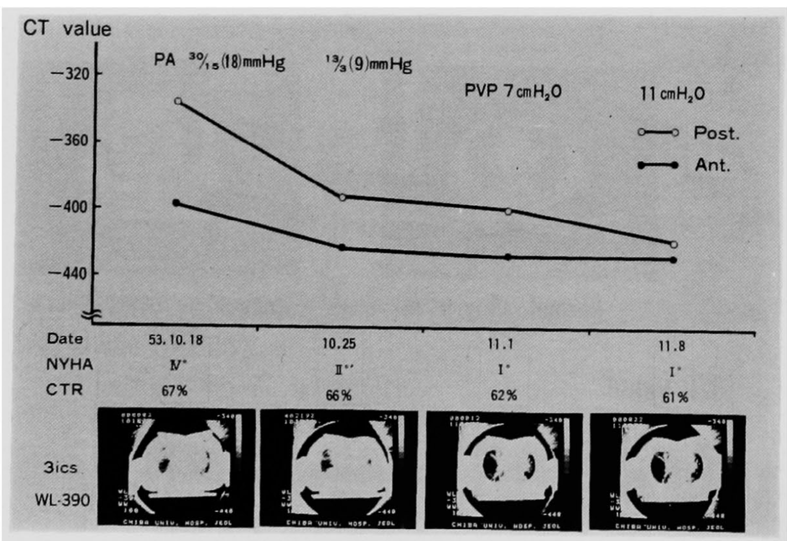

Fig. 5. Improvement of CT findings after successful treatment in a patient with acute left ventricular failure due to hypertensive cardiac disease. The mean pulmonary CT value decreased subsequently. Abbreviations: PA = pulmonary arterial pressure; PVP = peripheral venous pressure; Post. = posterior lung field; Ant. = anterior lung field; NYHA = NYHA functional classification; CTR = cardiothoracic ratio.

ley B-line. The cardiothoracic ratio was 67%. The pulmonary arterial pressure was 30/15 mmHg. The CT value was −386 in the anterior lung field and −335 in the posterior lung field at the third intercostal space. With bed rest, digitalis and diuretics, the chest X-ray and symptoms markedly improved.

The CT value decreased transiently as shown in Fig. 5. Three weeks later, the patient became practically asymptomatic, and the pulmonary CT value approached the norm.

4) Pulmonary CT values and the NYHA functional classification

Pulmonary CT values in 45 patients with congestive heart failure are shown along with their NYHA functional classification[14] in Fig. 6. The mean CT value of the anterior and posterior lung fields at the fourth intercostal space was -384.4 ± 15.2 in patients of NYHA functional class II, and -432.1 ± 8.1 in normal subjects. This difference was significant ($p<0.005$). With advancement in the NYHA functional classification class from III to IV, the pulmonary CT value increased from -371.5 ± 14.8 to -351.0 ± 24.2. Symptomatic severity paralleled the pulmonary CT value.

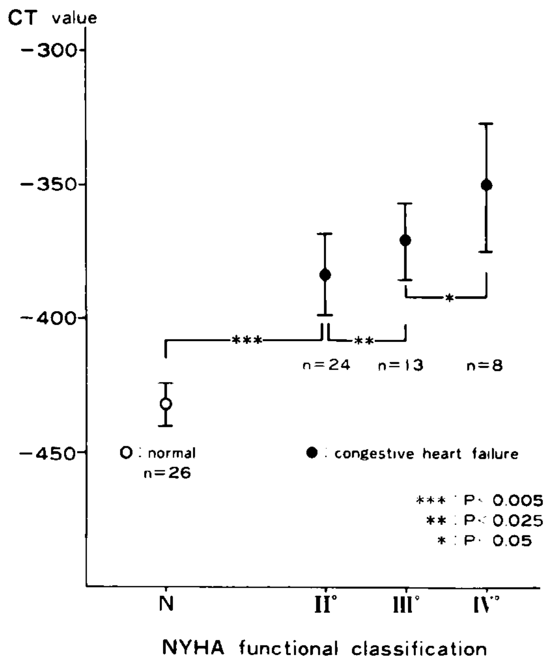

Fig. 6. Relationship between pulmonary CT value and NYHA functional classification. The pulmonary CT value increased in parallel with the NYHA functional classification, class III to IV.

5) Pulmonary CT value and chest X-ray

Chest X-ray findings in patients with congestive heart failure were classified into the following 4 groups as proposed by Kostuk et al[15]: A) no findings; B) pulmonary congestion showing pulmonary cephalization and centralization; C) interstitial edema showing septal lines (Kerley A, B lines), perivascular edema, peribronchial edema and hilar haze; D) alveolar edema showing a bat's wing pattern and periacinal rossette formation (Fig. 7).

The mean CT value of the anterior and posterior lung fields at the fourth intercostal space was -432.1 ± 8.1 in 26 normal subjects, -392.3 ± 15.1 in the pulmonary congestion group, -370.6 ± 14.0 in the interstitial edema group, and -349.2 ± 27.4 in the alveolar edema group. The pulmonary CT value in patients with congestive heart failure increased parallel to the progression of chest X-ray findings. The difference in CT value was statistically significant between the pulmonary congestion and interstitial edema groups ($p<0.005$), and the interstitial and alveolar edema groups ($p<0.1$).

In 10 patients with congestive heart failure, chest X-rays and pulmonary CT values were studied before and after treatment as indicated by the arrows in Fig. 7. The decrease in the CT value, noted after initiating treatment, was positively correlated with the improvement of chest X-ray. Even after com-

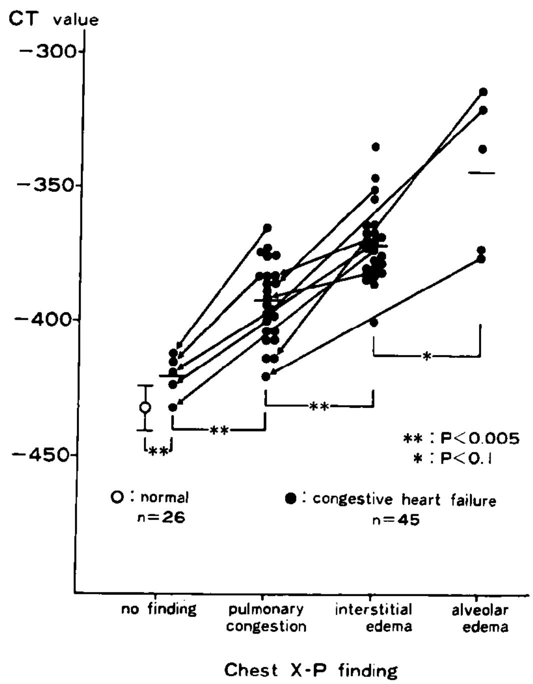

Fig. 7. Relationship between mean pulmonary CT value and chest X-ray findings.

plete regression of pathological signs in chest X-ray, the CT value was still significantly higher in the congestive heart failure group (−420.4±6.2) than in normal subjects (p<0.005).

6) Pulmonary CT values and pulmonary arterial wedge and mean pressures

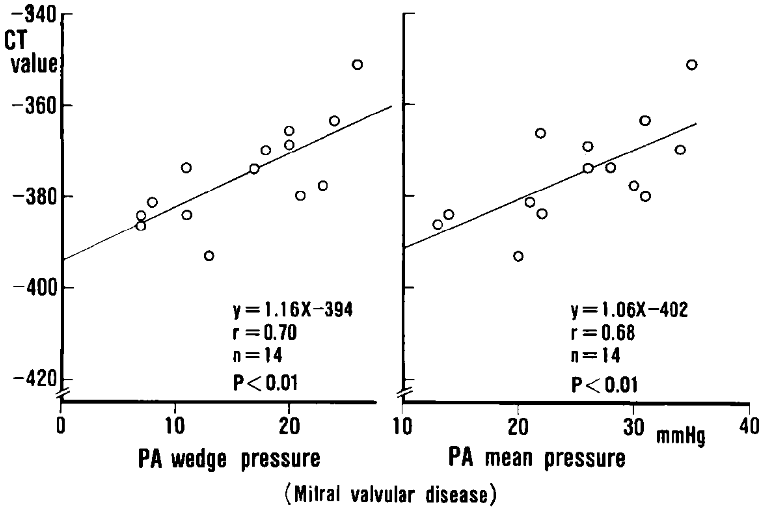

Fig. 8. Relationship between mean pulmonary CT value and pulmonary arterial wedge or mean pressures in patients with mitral valvular disease.

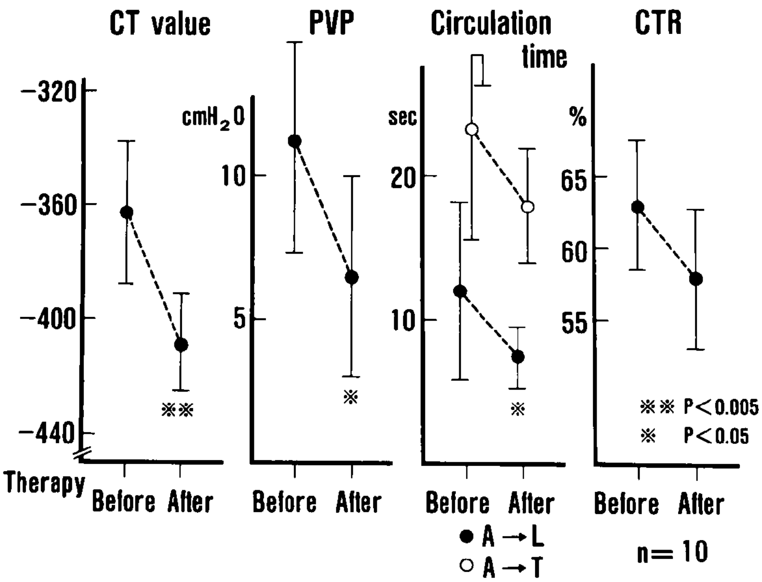

Fig. 9. The mean pulmonary CT value and hemodynamic parameters before and after treatment in patients with congestive heart failure. Abbreviations: A → L=arm-to-lung time; A → T=arm-to-tongue time.

A linear correlation was observed between pulmonary arterial wedge pressure (X) and mean CT value (Y) of the anterior and posterior lung fields ($r=0.70$, $y=1.16X-394$, $p<0.01$), and between pulmonary arterial mean pressure (X) and mean CT value (Y) ($r=0.68$, $y=1.06X-402$, $p<0.01$) (Fig. 8).

7) Pulmonary CT values and hemodynamic parameters before and after treatment

Fig. 9 shows the mean CT value of the anterior and posterior lung fields, peripheral venous pressure (PVP), circulation time (arm-to-lung and arm-to-tongue times) and cardiothoracic ratio (CTR) in 10 patients with congestive heart failure who responded favorably to treatment. The pulmonary CT value changed more significantly than any hemodynamic parameter ($p<0.005$). Therefore, the pulmonary CT value is apparently a very sensitive parameter indicating the effects of treatment.

Discussion

Since whole body CT can indicate the X-ray attenuation coefficient per unit volume as the CT value, pathological changes of pulmonary tissues such as congestion, infarction and retention of pleural effusion can be detected by pulmonary CT images.[16),17)] Furthermore, as our studies[5),6),18)-20)] demonstrated, the pulmonary water distribution and severity of pulmonary congestion in patients with congestive heart failure can be estimated quantitatively by the CT value, although there is a conspicuous lack of literature dealing with this topic.

Alfidi et al[16)] reported that hydrostatic pressure-induced changes in pulmonary vessel diameter alter the blood volume per unit of lung tissue.

Our observations clearly demonstrated that postural changes in CT value were gravity-dependent in normal subjects and patients with congestive heart failure, as expected from previous studies.[18)-20)]

The fact that the pulmonary CT value in the posterior lung field was slightly higher at the fourth than at the second intercostal space lends support to the view of Nakamura et al,[8)] i.e., acute experimental pulmonary edema appears first in the lower posterior lung.

Our previous study,[20)] carried out to investigate the absolute water content in the lung, revealed an excellent correlation between water content in a sponge and the CT value. When the water content was increased by 1%, the CT value rose by about 5 EMI units.

Since the difference between mean pulmonary CT values in patients with congestive heart failure and normal subjects was about 50 EMI units,

water content of the lung in these patients may be calculated to increase by about 600 Gm as we previously reported.[20]

Mccredie[21] and Luepker[22] showed that the pulmonary extravascular water volume determined by the double indicator method, was directly related to the pulmonary arterial pressure and left atrial mean pressure in patients with heart diseases. This, they suggested, was due to a shift in water distribution from intra-to extra-vascular spaces secondary to a decrease in left heart function. Our results obtained in patients with mitral valvular disease demonstrated a close correlation between pulmonary CT value and pulmonary arterial wedge pressure or pulmonary arterial mean pressure ($r=0.70$, $r=0.68$, respectively), which may likewise be caused by the mechanism proposed by Mccredie and Luepker.

It was found that the higher the grade of the NYHA functional classification, the greater was the mean pulmonary CT value of the anterior and posterior lung fields in patients with congestive heart failure. Luepker et al[22] also reported marked increases in extravascular water volume of the lung in patients of class II and III.

The fact that patients of class I without significant signs and symptoms of congestive heart failure still had a higher mean pulmonary CT value than normal subjects, suggests that the pulmonary CT value is a very sensitive parameter for the early detection of pulmonary congestion or edema.

Furthermore, the pulmonary CT value changed more significantly than any other parameter, including peripheral venous pressure, circulation time and cardiothoracic ratio, after treatment with digitalis and diuretics in patients with congestive heart failure. Thus, pulmonary CT value may be of clinical value in monitoring the progress of treatment in patients with heart failure.

Moreover, the pulmonary CT has the additional advantages that it may be estimated quite easily, quickly, repeatedly, and noninvasively.

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