Intensive Care Med (2001) 27: 631–639
DOI 10.1007/s001340100877

REVIEW

**Antonio Pesenti**
**Paola Tagliabue**
**Nicolò Patroniti**
**Roberto Fumagalli**

# Computerised tomography scan imaging in acute respiratory distress syndrome

Received: 7 January 2001
Final revision received: 7 January 2001
Accepted: 7 January 2001
Published online: 6 March 2001


A. Pesenti (✉) · P. Tagliabue · N. Patroniti
Anaesthesia and Intensive Care Department,
Università degli Studi Milano-Bicocca,
Ospedale Nuovo S. Gerardo,
via G. Donizetti 106,
20052 Monza, Milan, Italy
E-mail: antonio.pesenti@unimib.it
Phone: +39-039-2333291
Fax: +39-039-2332297

R. Fumagalli
Paediatric Intensive Care,
Ospedali Riuniti di Bergamo,
Largo Barozzi 1,
24128 Bergamo, Italy

**Abstract** Computerised tomography (CT) is being used with increasing frequency in acute respiratory distress syndrome (ARDS) patients. This brief review will discuss some of the clinical insights that a CT scan can offer. A large number of CT scan studies have provided new insights into the pathophysiology of ARDS and of mechanical ventilation, and are particularly focused on the recruitment-derecruitment phenomenon. To this end, newer fast CT scan technology promises a dynamic, rather than a static view of lung ventilation.

**Key words** Computerised tomography (CT) · CT scan · Acute respiratory distress syndrome (ARDS) · Pulmonary ARDS · Extrapulmonary ARDS · Intensive care unit

## Introduction

The computerised tomography (CT) scan has substantially improved our understanding of the acute respiratory distress syndrome (ARDS). The following review is not intended to cover the entire topic, but rather to provide a selected update, albeit providing background information where necessary.

The conventional portable chest X-ray remains the most commonly used diagnostic imaging tool for following the evolution of lung disease in the intensive care unit (ICU) patient [1, 2, 3, 4]. Though the efficacy and effectiveness of routine daily chest X-rays are still under debate, current practice in most ICUs is to obtain daily chest X-rays [5, 6]. This practice has been claimed to have an important impact on diagnosis, prognosis and therapy [7], though whether this is cost-effective remains unproved. To avoid pitfalls in interpretation, various means of improving reproducibility and standardisation have been suggested [8]. For example, digital techniques have been claimed to improve chest imaging in the ICU patient, however no clear evidence has so far been produced to justify their widespread use [9, 10]. In the meantime, the CT scan has become a very popular tool in the ARDS patient. Its cost-effectiveness in clinical use has still to be demonstrated, even though some investigators consider it as part of the routine management of ARDS [11].

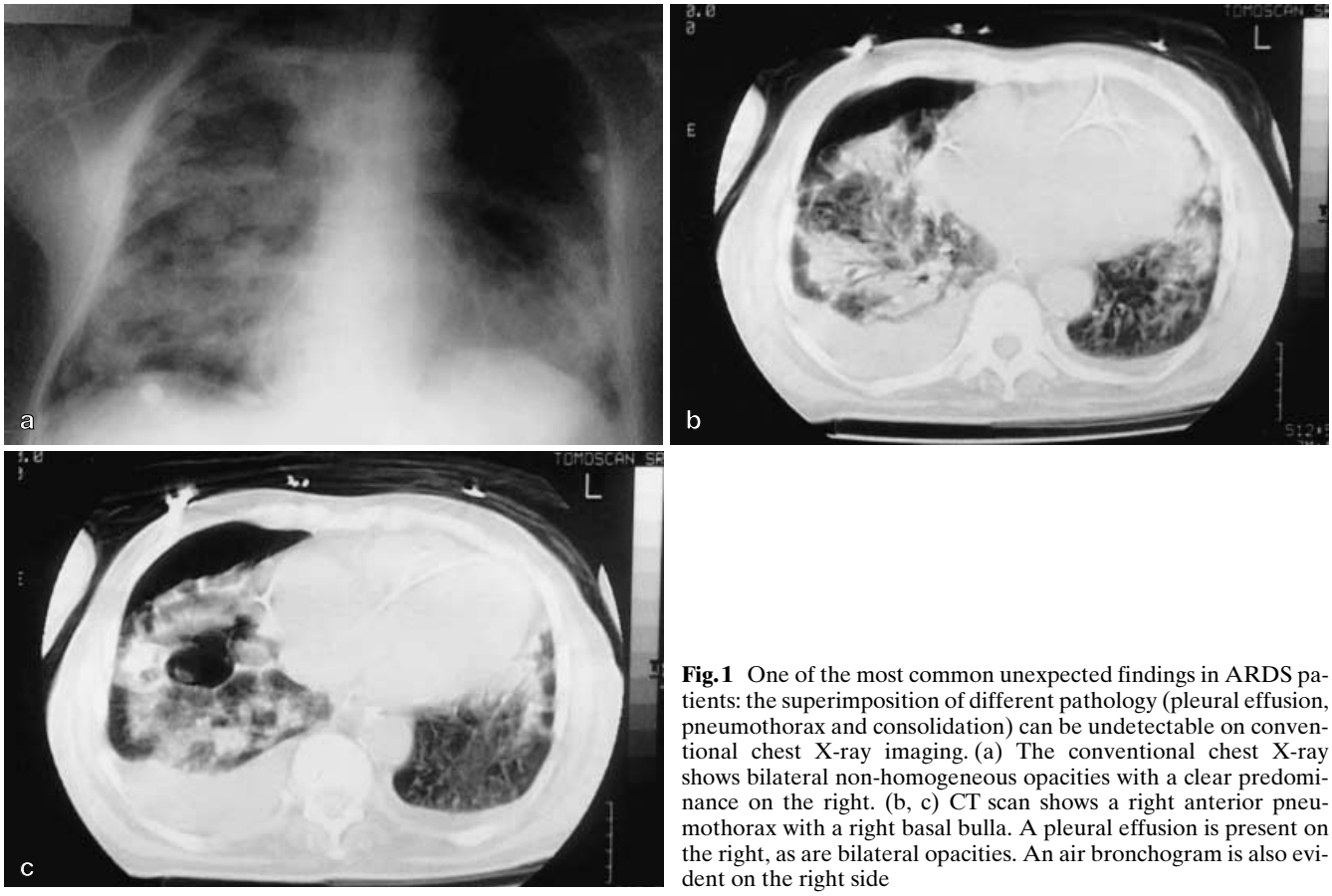


**Fig. 1** One of the most common unexpected findings in ARDS patients: the superimposition of different pathology (pleural effusion, pneumothorax and consolidation) can be undetectable on conventional chest X-ray imaging. (a) The conventional chest X-ray shows bilateral non-homogeneous opacities with a clear predominance on the right. (b, c) CT scan shows a right anterior pneumothorax with a right basal bulla. A pleural effusion is present on the right, as are bilateral opacities. An air bronchogram is also evident on the right side

## Advantages and limitations

The CT scan offers many advantages. It provides a cross-sectional display, it avoids superimposition of different structures (Fig. 1) and it allows accurate measurement of the extent of the abnormalities and of the density of the structures of interest.

On the other hand, it does carry some major disadvantages. It is a costly resource of limited availability, it exposes the patient to a higher amount of radiation compared to a standard chest X-ray, it is not normally available at the bedside and, therefore, it exposes the patient to the risk of transfer to the CT suite. Exposure to radiation remains an important concern. For this reason, even if the entire lung can be covered by a spiral CT scan for pathophysiological studies, our group has most often limited the study to three sections, namely apex, hilum and base; and sometimes to only one section, considering this sample to be representative of the entire lung [12]. Transfer to the CT suite also constitutes a definite risk: some patients are distinctly better when they are not moved from the ICU environment. A useful examination should not in itself be sufficient to justify an unbearable risk. However, on most occasions, an expert transfer team and a well-equipped CT suite will enable a scan to be performed with appropriate safety [13].

## Morphological description

The detailed and accurate images provided by CT technology have encouraged the intensivist to use CT scanning more and more frequently, mainly to improve description of the pathological process. Early observations by Maunder and Gattinoni [14, 15] showed that ARDS is not the diffuse and homogeneous process depicted by conventional chest X-rays. Indeed, the title of Maunder's original report is "Preservation of normal lung regions in ARDS" and it directed the reader's attention to the problem of regional inhomogeneity. Patchy infiltrates are interspersed with lung areas of normal appearance.

The morphological description of the CT scan includes the recognition of normally aerated lung, areas of increased density with still recognisable vessels (ground glass opacification) and areas of increased density with vessels that are no longer identifiable (consolidation). While ground glass areas have quite a diffuse distribution over the entire lung field, consolidation is

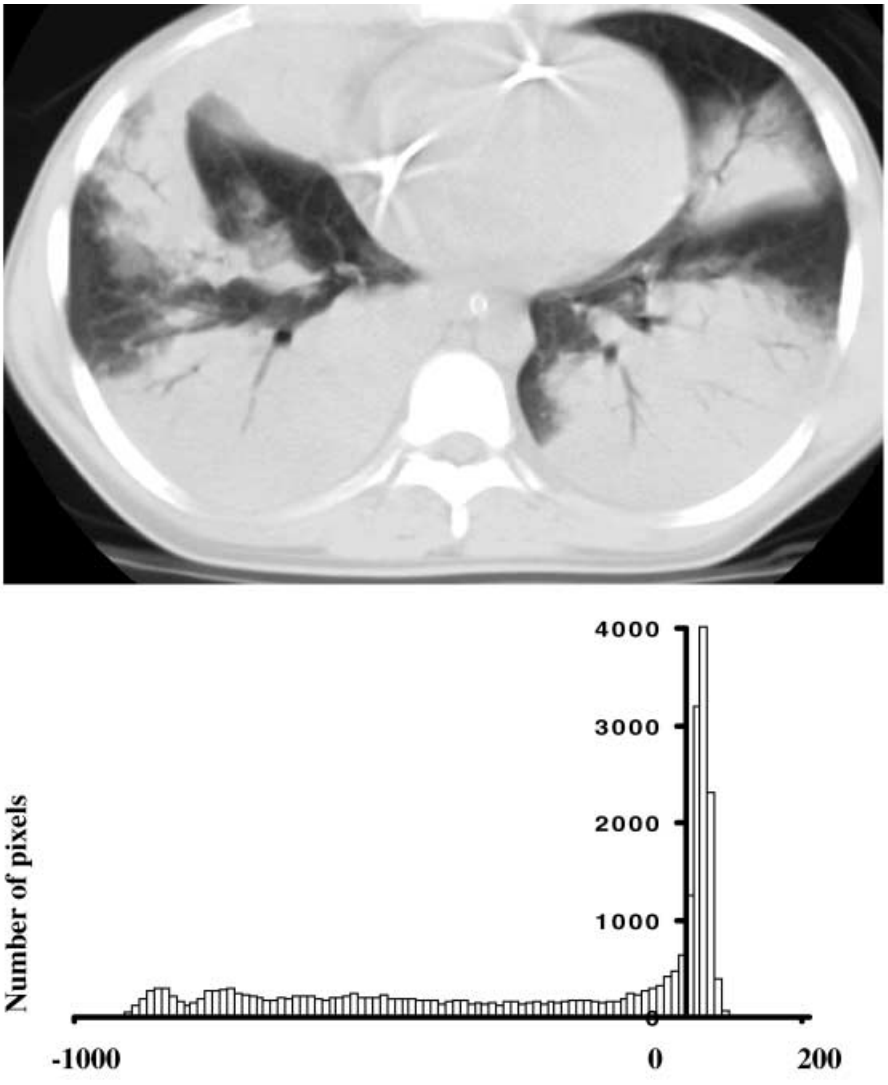


**Fig. 2** A typical $ARDS_p$ pattern: dense consolidation mainly in the dependent regions is present in this patient with bacterial pneumonia. The CT histogram is characterised by a high frequency peak of CT density corresponding to consolidated tissue

mainly located in the dependent (dorsal) regions [16, 17]. The apical regions are most often spared from major consolidation.

Air bronchograms as well as bronchial dilatation are also common findings in both acute lung injury (ALI) and ARDS [17, 18]. Acute inflammation, as well as the early onset of interstitial fibrosis, are possibly involved in the development of bronchial dilatation. Furthermore, pleural effusions, not usually considered as a common trait of ARDS, are present in the vast majority of patients affected by the syndrome.

## Differences in acute respiratory distress syndrome from pulmonary and extrapulmonary causes

Differences in pathophysiology between ARDS secondary to direct pulmonary disease ($ARDS_p$), e.g. pneumonia, and ARDS secondary to extrapulmonary disease ($ARDS_{exp}$), e.g. sepsis, have been recently described [19, 20]. Gattinoni et al. [19] observed that $ARDS_p$ patients showed less evidence of lung recruitment when increased levels of positive end-expiratory pressure (PEEP) were applied in comparison to $ARDS_{exp}$ patients. Goodman et al. [17] studied the morphological appearance of the CT scan in $ARDS_p$ and $ARDS_{exp}$ patients. The former was more often asymmetrical with focal areas of dense consolidation (Fig. 2); on the other hand, $ARDS_{exp}$ revealed a predominantly symmetrical pattern with prevalence of ground glass areas (Fig. 3). It is important to emphasise that the two types of lesion do coexist, though to different extents, in the same patient. Moreover, the amount of lung consolidation is significantly related to the severity of the disease as well as to the subsequent mortality [17].

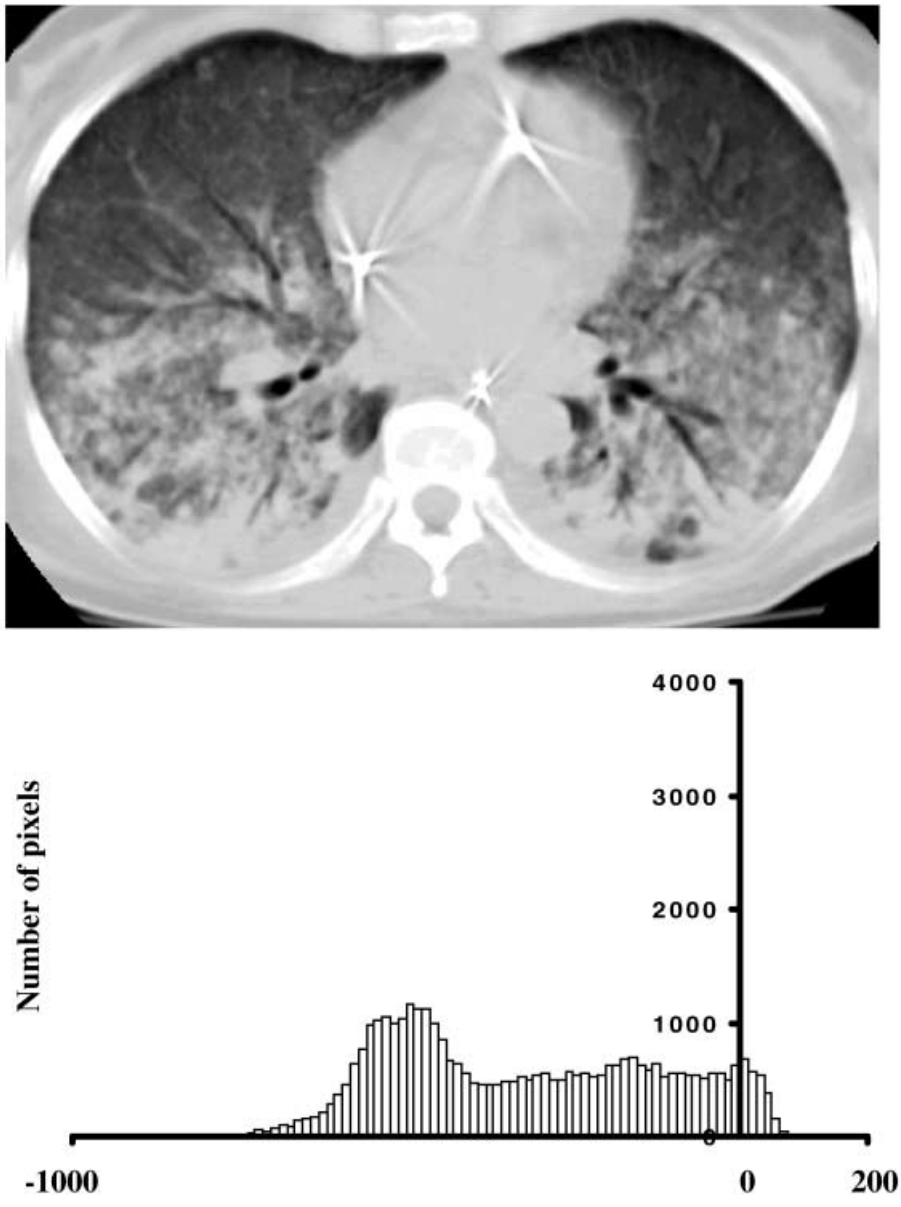


**Fig. 3** A typical $ARDS_{exp}$ pattern: diffuse ground glass appearance with some areas of consolidation in this patient with peritonitis. Frequency distribution of CT density is more homogeneously distributed, showing a prevalence of CT density corresponding to ground glass tissue

## Computerised tomography scan follow-up in patients recovering from acute respiratory distress syndrome

Computerised tomography abnormalities at long-term follow-up (weeks to months) in survivors of ARDS have also been investigated recently [21]. The most prevalent CT abnormality in patients recovering from ARDS was a coarse reticular pattern with distortion of lung architecture that was predominantly distributed in non-dependent areas. It has been suggested that this reticular pattern may constitute the evolution of ground glass areas. This observation could suggest that collapsed or consolidated areas are relatively protected from the iatrogenic effect of mechanical ventilation. On the contrary, non-dependent areas could be preferentially exposed to alveolar overdistension.

Another frequent finding at follow-up is bronchial dilatation. In a study by Howling at al. [18], bronchial dilatation persisted at follow-up in 92% of the lobes in which it was present during the acute phase. Moreover, a reticular pattern with distortion of lung architecture was observed in the same lobes presenting with bronchial dilatation. These observations support the hypothesis that bronchial dilatation during the acute phase of ARDS may be the consequence of early fibrosis.

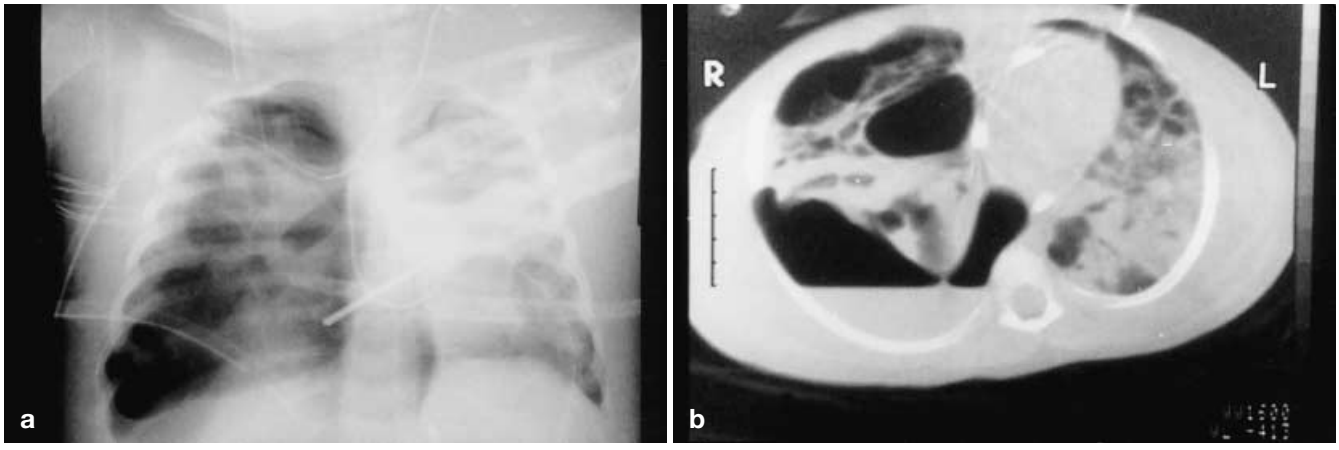


**Fig. 4** Images taken from a nearly drowned 3-year-old girl who was resuscitated and subsequently developed ARDS, for which she required extracorporeal carbon dioxide removal. (a) The distribution of the pneumothorax appears to be totally unpredictable from the plain chest X-ray: chest tubes are unable to drain the air collection; (b) a CT scan shows posterior hydropneumothorax in the right hemithorax with pulmonary collapse associated with a right anterior pneumothorax. Bilateral opacities with bullae are diffusely represented

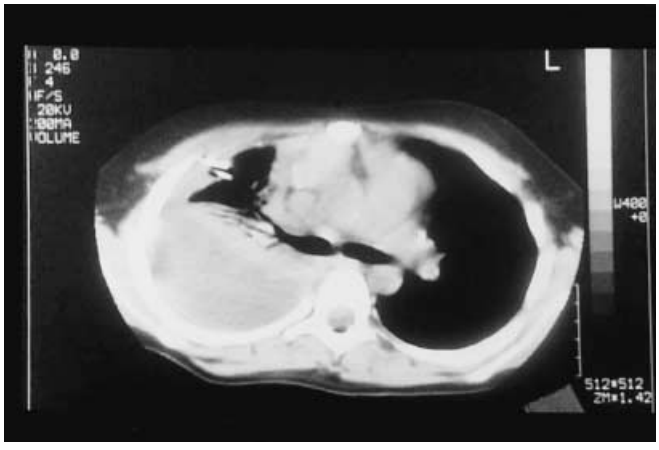


**Fig. 5** A CT scan can solve clinical problems related to an unexplained clinical course: in this case a 4-year-old boy admitted with pneumonia developed severe hypoxaemia ($PaO_2/FIO_2$ ratio of 150). Several thoracocenteses did not result in the removal of the pleural collection. CT examination showed a large right pleural effusion with non-homogeneous content; the pleural drainage was located anteriorly and unable to drain the collection; most of the lung parenchyma was compressed by the collection; correct localisation of the pleural effusion allowed the positioning of a double lumen chest tube and the intrapleural administration of streptokinase

## Recognising and treating specific lesions by computerised tomography scan

As previously stated, the CT scan can add additional information to that provided by conventional X-rays. This includes a detailed distribution of lesions and an accurate topographical localisation.

### Pneumothorax and pleural effusion

An anterior pneumothorax overlying an area of increased density due to consolidation or pleural effusion is often difficult to diagnose from a plain chest X-ray film alone. In such cases, as well as with loculate tension pneumothoraces, CT scan can easily lead to their identification. Drainage can also be facilitated under CT scan guidance. As mentioned previously, CT scanning has also demonstrated that mild-to-moderate pleural effusions are regularly found in ARDS [17] (Figs. 4 and 5).

### Bronchoalveolar lavage

Computerised tomography scan imaging may be useful in directing sampling procedures such as bronchoalveolar lavage (BAL), brushing or biopsy. However, the importance and the implication of this use of the CT scan is still undefined.

### Abscesses and blebs

Focal areas of intraparenchymal radiolucency are common in ARDS. Their detection and appearance can have important clinical implications. The presence of a fluid level may suggest the evolution of an infectious process towards abscess formation that may require specific therapeutic manoeuvres [22, 23] (Fig. 6). Evidence

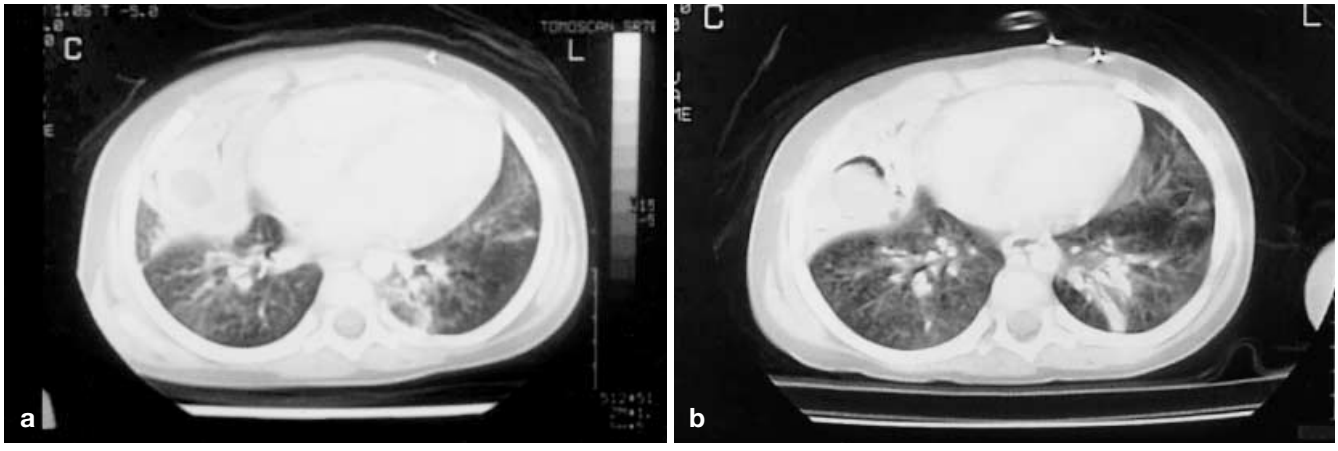


**Fig. 6** ARDS in haematological malignancy represents a particularly challenging diagnostic dilemma. The CT scan can detect signs of fungal infection much earlier than conventional chest X-ray imaging. In this 2-year-old girl with erythrophagocytic histiocytosis and pulmonary insufficiency, CT scanning revealed (a) two abscesses in the right lung and (b) one with an air contour. In the previous absence of positive microbiology or serology, CT localisation allowed percutaneous needle aspiration that revealed *Aspergillus fumigatus*

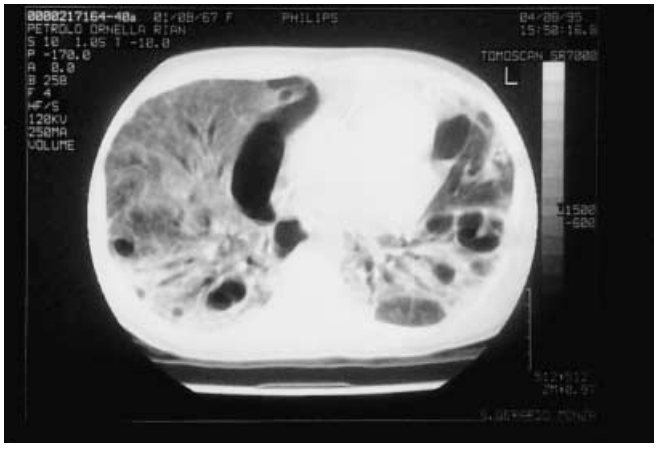

**Fig. 7** A CT scan is mandatory in very aggressive lung disease where the air collection can show an unusual distribution. In this case of staphylococcal pneumonia complicating an episode of pulmonary embolism in a 23-year-old woman, a loculate air collection deforms the right heart profile. Haemodynamic monitoring had shown high filling pressures and a low cardiac output. Percutaneous chest drainage was performed under CT guidance; opacities, air bronchograms and bullae were present on both the left and right sides

of intraparenchymal air collections (pneumatoceles, bullae) has been shown to be associated with both the duration of disease and the barotrauma effect of mechanical ventilation [24] (Fig. 7).

### Cardiogenic versus non-cardiogenic pulmonary oedema

Differentiation between cardiogenic and non-cardiogenic pulmonary oedema can sometimes prove difficult, particularly in mechanically ventilated patients, when changes in intrathoracic pressure challenge the standard diagnostic criteria based on left ventricular filling pressures. The perihilar distribution of pulmonary oedema of cardiogenic (Fig. 8), fluid overload and renal origins, as well as the poor definition of peripheral vessels and thickening of interlobar fissures and septal lines may prove very helpful in determining the diagnosis [25].

## Quantitative analysis

Acute respiratory distress syndrome researchers have exploited the CT scan as an accurate method of measuring regional radiographic density [26], rather than using it as a fascinating and powerful method of imaging the chest [27].

A CT scan image consists of an array of small squares (pixels), each one representing the two-dimensional average of the radiographic density of a small volume (voxel) having the pixel as the base and the thickness of the scan section as its length. Radiographic density is the property of substances to absorb X-radiation. In spite of many limitations, radiographic density is very well correlated to physical density (i.e. weight per unit volume).

Radiographic density is usually expressed in Hounsfield units. These are scaled from air (–1000 H) to water (0 H) to bone which usually has a positive density above 1000 H. When a given voxel has an average density of –500 H, it is therefore reasonably accurate to assume that its radiographic density, and therefore its physical density, is halfway between air and water. In the case of the lung, we can make the further assumption that it is made up mainly of air and water, the content of other substances being limited to a small percentage. There-

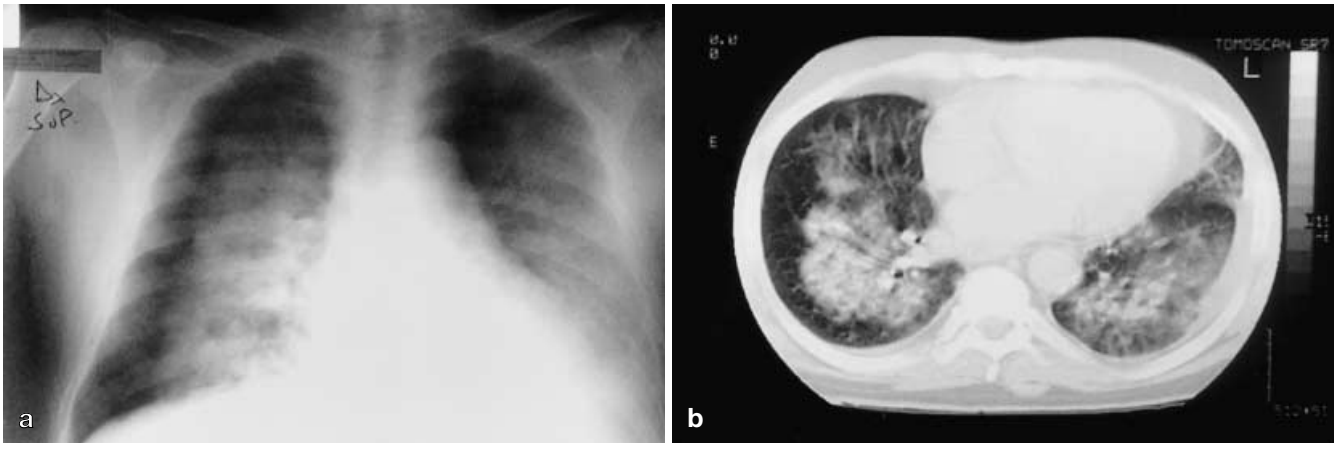


**Fig. 8** This patient was admitted with respiratory distress after a few days of low grade fever and no chest pain. Plain chest X-ray raised the possibility of a right pneumothorax. In the right hemithorax opacities spared the peripheral region of the lung; in the left hemithorax the opacities were more diffuse. Two-dimensional echocardiography revealed severe mitral regurgitation. The CT scan clearly shows the butterfly distribution of the opacities

fore, when the Hounsfield number is –500 we can assume that the volume of the examined voxel is made up of 50 % water and 50 % air (volume/volume). If the Hounsfield number is –700, as in the normal lung, 70 % will be air and 30 % water (or tissue). On the other hand, when the Hounsfield number is –200, as in ARDS, we can assume the air content to be only 20 % or thereabouts.

The recognition of the CT scan as an accurate way of measuring the physical density of specific regions of the lung (in the order of 1 mm × 1 mm × 1 to 10 mm) led to an entirely new line of investigation into the pathophysiology of ARDS and the effects of different ventilatory strategies. Quantitative analysis showed that the ARDS lung is very heavy, weighing 2–3 times that of a normal lung [28]. The content of air is greatly decreased, to values 20–30 % of normal. Pelosi et al. suggested that total lung volume (tissue + air) is substantially unchanged in ARDS [29]. However, more accurate measurements taken by Puybasset et al. [27] showed a decrease in total lung volume, mainly due to a decrease in the apex to diaphragm length, with cephalad movement of the diaphragm. Most importantly, the CT scan shows that the ARDS lung is not homogeneous, with increased densities mainly located in the dependent lung regions (i.e. dorsal in the supine patient). When the patient is positioned prone, densities move from dorsal to ventral, following the gravitational field [30].

Gattinoni has ascribed this phenomenon to the effects of the increased lung weight and to a corresponding increase in the pleural pressure gradient. To simplify, the alveoli at the bottom of the lung are compressed by the alveoli at the top. Since the ARDS lung tissue is oedematous and heavy, the weight that each alveolus has to bear is increased and air is squeezed out from the alveoli at the bottom [29]. Each alveolus is compressed by the superimposed pressure generated by the weight of the superimposed structures. The heavier the lung, the higher the superimposed pressure. Regional analysis of the CT scan is therefore suggestive of a homogeneously diseased lung with a concomitant non-homogeneous distribution of densities, since the gas content progressively decreases from top to bottom due to compression atelectasis. Puybasset has recently shown that densities are not only distributed along the ventral to dorsal axis, but from cephalad to caudal as well, due to a preferential loss of volume and increased density of the lung lower lobes [27]. This is possibly related to increases in abdominal pressure.

## Measuring recruitment

Computerised tomography scan analysis is a powerful tool for measuring lung recruitment, a process most often affected by changes in intrapulmonary pressure. Lung recruitment can be quantified by measuring how much non-aerated tissue becomes aerated by the application of, say, 10 $cmH_2O$ PEEP. This can be done, as suggested by Puybasset, by measuring the change in volume (number of voxels) of non-aerated tissue [27]. Alternative approaches include computing the changes in weight (in grams) of normally aerated tissue [31] or computing the weight of consolidated tissue [27, 28, 29, 30, 31, 32]. It is reasonable to suppose that measurements based on changes of weight are more accurate than those based upon changes in volume. Neither method, however, takes into account possible topographical changes in blood volume distribution.

## Positive end-expiratory pressure and recruitment

The application of PEEP is generally associated with the clearing of radiographic density and a decrease in the amount of consolidated tissue. Considering the lung to behave as a fluid-like system, it is possible to estimate the "superimposed pressure" (SPl, i.e. the hydrostatic pressure superimposed on a given lung level) from the density and height of the tissue on top of it. Gattinoni et al. showed that the amount of PEEP required to recruit a given level of the lung is directly related to the SPl acting on that level: the higher the SPl, the higher the PEEP required [28]. They suggested that increases of lung weight and of SPl play an important role in inducing lung collapse, and that one of the main mechanisms through which PEEP recruits collapsed lung is by counterbalancing SPl. In another study, Gattinoni et al. suggested that cyclical opening and collapsing related to the tidal volume progressively decreased with increasing PEEP. Moreover, at constant tidal volume they found that the recruitment effect of PEEP was directed at the top levels of the lung at lower PEEP, and moved downward to the bottom levels as the PEEP level was increased from 0 to 20 $cmH_2O$ [32]. To this top-to-bottom (ventral to dorsal) effect, Puybasset et al. have added the concept of a cephalad to caudal distribution, with a preferential effect of PEEP on the cephalad (upper) lobes, rather than on the lower, mainly collapsed, lobes. If PEEP is applied high enough to recruit the dorsal regions and lower lobes, both the ventral regions and the upper lobes become relatively overdistended [27].

## Tidal volume and recruitment

During tidal ventilation the lung may collapse at end-expiration, and reopen at the end of inspiration. This cyclic opening and closing during tidal ventilation has been implicated as one of the mechanisms causing VILI (ventilator-induced lung injury). It has therefore been investigated by comparing CT scans taken at end-inspiration with scans taken at end-expiration. As described above, Gattinoni has shown that the amount of recruitment-derecruitment decreases by increasing PEEP at constant tidal volume. This is achieved by affecting the distribution of the tidal volume. By increasing PEEP from 0 to 20 $cmH_2O$, the upper regions of the lung become overdistended and less compliant, favouring the distribution of tidal volume to the lower regions of the lung. In spite of this overdistension, the overall effect is that PEEP makes gas distribution more homogeneous [32].

## Pressure-volume curve

In ARDS the pressure-volume curve has been described as often being characterised by a lower inflection point (LIP) and an upper inflection point (UIP). The LIP could correspond to the pressure at which recruitment takes place, while the UIP is the pressure at which alveoli start to be overdistended, approaching their mechanical limits [33].

Even if this concept has been challenged [34, 35], the LIP in particular has been used as an important guide in setting airway pressure during mechanical ventilation [36]. Gattinoni showed [31] that the ratio of changes in compliance at pressures below and above the LIP was related to the ratio of normally aerated tissue. Moreover, compliance was proportional to the amount of aerated tissue, while it was unrelated to the amount (weight) of consolidated tissue. Vieira et al. have recently shown major differences in patients with and without a LIP [11]. In patients without a LIP the application of PEEP resulted in lung overdistension rather than in recruitment, as was the case in those with a LIP. Overdistension induced by PEEP was typical of patients without a LIP [11]. However, there are not yet enough data to support the hypothesis that CT scanning should be used routinely to optimise mechanical ventilation [37].

## Conclusions

In the last 15 years the CT scan has contributed significantly to our understanding of the pathophysiology of ARDS and of mechanical ventilation. Until now the CT scan has provided static equilibrium images; recent technological advances have opened up a new field of dynamic studies of lung morphology obtained by fast CT scan techniques. Experimental studies have already been conducted to evaluate the dynamics of lung collapse and recruitment [38].

The strength of CT scan lies in its double feature of powerful imaging tool and accurate quantitative instrument to measure regional physical density. The CT scan is also moving from an investigational tool to become part of the standard clinical management of complex ARDS patients. Its clinical role, though still awaiting a precise definition, is expanding very quickly: this process would be facilitated by the availability of bedside CT scans.

## References


1. Pelosi P, Brazzi L, Gattinoni L (1999) Diagnostic imaging in acute respiratory distress syndrome. Curr Opin Crit Care 5: 9–16
2. Pelosi P, Crotti S, Brazzi L, Gattinoni L (1996) Computed tomography in adult respiratory distress syndrome : what has it taught us? Eur Respir J 9: 1055–1062
3. Desai SR, Hansell DM (1997) Lung imaging in the adult respiratory distress syndrome: current practice and new insights. Intensive Care Med 23: 7–15
4. Bombino M, Gattinoni L, Pesenti A, Pistolesi M, Miniati M (1991) The value of portable chest roentgenography in adult respiratory distress syndrome. Comparison with computed tomography. Chest 100: 762–769
5. Henschke Cl, Pasternak GS, Schroeder S, Hart KK, Herman PG (1983) Bedside chest radiography: diagnostic efficacy. Radiology 149: 23–26
6. Bekemeyer WB, Crapo RO, Calhoon S, Cannon CY, Clayton PD (1985) Efficacy of chest radiography in a respiratory intensive care unit: a prospective study. Chest 88: 691–696
7. Strain DS, Kinasewitz GT, Vereen LE, George RB (1985) Value of routine daily chest X-rays in medical intensive care unit. Crit Care Med 13: 534–536
8. Milne ENC, Pistolesi M, Miniati M, Giuntini C (1985) The radiologic distinction of cardiogenic and non cardiogenic edema. Am J Roentgenol 144: 879–894
9. Sonoda M, Takano M, Miyahare J, Kato H (1983) Computed radiography utilising scanning laser simulated luminescence. Radiology 148: 833–838
10. Jennings P, Padley SPG, Hansell DM (1992) Portable chest radiography in intensive care: a comparison of computed and conventional radiography. Br J Radiol 65: 852–856
11. Vieira SR, Puybasset L, Lu Q, et al. (1999) A scanographic assessment of pulmonary morphology in acute lung injury. Am J Respir Crit Care Med 159: 1612–1623
12. Tagliabue P, Giannatelli F, Vedovati S, et al. (1998) Lung CT scan in ARDS: are three sections representative of the entire lung? Intensive Care Med 24 (Suppl 1):93
13. Wallace PGM, Ridley SA (1999) Transport of critically ill patients. BMJ 319: 368–371
14. Maunder RJ, Shuman WP, McHugh JW, Marglin SI, Butler J (1986) Preservation of normal lung regions in the adult respiratory distress syndrome: analysis by computed tomography. JAMA 255: 2463–2465
15. Gattinoni L, Mascheroni D, Torresin A, et al. (1986) Morphological response to positive end expiratory pressure in acute respiratory failure. Computerized tomography study. Intensive Care Med 12: 137–142
16. Gattinoni L, Pelosi P, Pesenti A, et al. (1991) CT scan in ARDS: Clinical and physiopathological insights. Acta Anaesthesiol Scand 35 (Suppl 95):87–96
17. Goodman LR, Fumagalli R, Tagliabue P, et al. (1999) Adult respiratory distress syndrome due to pulmonary and extrapulmonary causes: CT, clinical, and functional correlations. Radiology 213: 545–552
18. Howling SJ, Evans TW, Hansell DM (1998) The significance of bronchial dilatation on CT in patients with adult respiratory distress syndrome. Clin Radiol 53: 105–109
19. Gattinoni L, Pelosi P, Suter M, Peduto A, Vercesi P, Lissoni A (1998) Acute respiratory distress syndrome due to pulmonary and extrapulmonary disease: different syndromes? Am J Respir Crit Care Med 158: 3–11
20. Ranieri VM, Brienza N, Santostasi S, et al. (1997) Impairment of lung and chest wall mechanics in patients with acute respiratory distress syndrome: role of abdominal distension Am J Respir Crit Care Med 156: 1082–1091
21. Desai SR, Wells AU, Rubens MB, Evans TW, Hansell DM (1999) Acute respiratory distress syndrome: CT abnormalities at long-term follow-up. Radiology 210: 29–35
22. Snow N, Bergin KT, Horrigan TP (1990) Thoracic CT scanning in critically ill patients: information obtained frequently alters management. Chest 97: 1467–1470
23. Ho ET, Peh WC (1996) Clinics in diagnostic imaging. Acute respiratory distress syndrome (ARDS) secondary to intra-abdominal sepsis. Singapore Med J 37: 653–657
24. Gattinoni L, Bombino M, Pelosi P, et al. (1994) Lung structure and function in different stages of severe adult respiratory distress syndrome. JAMA 271: 1772–1779
25. Stark P, Jasmine J (1989) CT of pulmonary edema. Crit Rev Diagn Imaging 29 (3):245–255
26. Drummond GB (1998) Computed tomography and pulmonary measurements. Br J Anaesth 80: 665–671
27. Puybasset L, Cluzel P, Chao N, Slutsy AS, Coriat P, Rouby JJ (1998) A computed tomography scan assessment of regional lung volume in acute lung injury. Am J Respir Crit Care Med 158: 1644–1655
28. Gattinoni L, Pesenti A, Bombino M, et al. (1988) Relationships between lung computed tomographic density, gas exchange and PEEP in acute respiratory failure. Anesthesiology 69: 824–832
29. Pelosi P, D'Andrea L, Vitale G, Pesenti A, Gattinoni L (1994) Vertical gradient of regional lung inflation in adult respiratory distress syndrome. Am J Respir Crit Care Med 149: 8–13
30. Gattinoni L, Pelosi P,Vitale G, Pesenti A, D'Andrea L, Mascheroni D (1991) Body position changes redistribute lung computed-tomographic density in patients with acute respiratory failure. Anesthesiology 74: 15–23
31. Gattinoni L, Pesenti A, Avalli L, Rossi F, Bombino M (1987) Pressure-volume curve of total respiratory system in acute respiratory failure. Computed tomographic study. Am Rev Respir Dis 136: 730–736
32. Gattinoni L, Pelosi P, Crotti S, Valenza F (1995) Effects of positive end-expiratory pressure on regional distribution of tidal volume and recruitment in adult respiratory distress syndrome. Am J Respir Crit Care Med 151: 1807–1814
33. Dambrosio M, Roupie E, Mollet JJ, et al. (1997) Effects of positive end-expiratory pressure and different tidal volumes on alveolar recruitment and hyperinflation. Anesthesiology 87: 495–503
34. Mergoni MA, Martelli A, Volpi S, Primavera S, Zuccoli P, Rossi A (1997) Impact of positive end-expiratory pressure on chest wall and lung-pressure curve in acute respiratory failure. Am J Respir Crit Care Med 156: 846–854
35. Hickling KG, Henderson SJ, Jackson R (1990) Low mortality associated with low volume pressure limited ventilation with permissive hypercapnia in severe adult respiratory distress syndrome. Intensive Care Med 16: 372–377
36. Amato MB, Barbas CS, Medeiros DM, Magaldi RB, Schettino GP, Lorenzi-Filho G (1998) Effect of a protective-ventilation strategy on mortality in acute respiratory distress syndrome. N Engl J Med 5: 347–354
37. Brunet F, Jeanbourquin D, Monchi M, et al. (1995) Should be mechanical ventilation be optimized to blood gases, lung mechanics, or thoracic CT scan? Am J Respir Crit Care Med 152: 524–530
38. Neumann P, Berglund JE, Mondejar EF (1998) Effect of different pressure levels on the dynamics of lung collapse and recruitment in oleic-induced lung injury. Am J Respir Crit Care Med 158: 1636–1643