Modern methods of assessment of lung aeration during mechanical ventilation

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Abstract

Despite the fact that several modes of ventilation are being used, it is not always possible to maintain adequate parameters of gas exchange. In order to provide proper ventilation, it is necessary to assess the lung function. The aim of this article is to present different methods of assessment of lung aeration including its advantages, disadvantages and possibilities for implementation in clinical practice. Computed tomography provides information regarding morphology and aeration of lung tissue, but has several limitations: necessity of patients transportation, it cannot be performed in a continuous manner, and a quantitative assessment of picture seems to be rather complicated. Ultrasonography is widely used in intensive care medicine, which is a noninvasive and bedside method. It gives the opportunity to assess an investigated organ in real time. Its clinical utility in patients with ARDS was proved by Lichtenstein at.al.

Another technology which has been implemented for the purpose of lungs visualization is electrobioimpedancy (EIT). This new method consists of continuous monitoring of chest electrobioimpedancy changes due to its air content. Unlike to techniques mentioned above, lung images generated with EIT do not provide any information about morphology of affected tissue.

The method which indirectly describes the sum of lung interactions is the assessment of quasi-static P/V curve. This method provides information allowing to draw conclusions regarding the usefulness of recruitment maneuvers, but does not provide information regarding the nature of morphologic changes and their location.

In the search for the ideal method of lung aeration assessment, it is necessary to define its characteristics, such as noninvasiveness, availability and visualization of tissue morphologic changes in real time.

Key words: mechanical ventilation; lung aeration, assessment; computed tomography; lung ultrasound; pressure/volume; loop; electrical impedance tomography

The majority of patients treated in intensive care units require mechanical ventilation, and adequate gas exchange is essential for optimal oxygenation of arterial blood. However, in some cases, despite the use of various modes of mechanical ventilation, satisfactory parameters of oxygenation cannot be provided. To improve the effectiveness of ventilation, assessment of lung aeration is found useful. The basic methods of clinical evaluation of the function of lungs and the extent of their aeration include auscultation and radiography. The evaluation of acoustic phenomena accompanying respiration is a subjective method of low specificity whereas radiological tests are of low sensitivity in many clinical situations. Therefore, new diagnostic methods are needed to help clinicians for objective and safe determination of the pathomechanism impairing lung aeration.

During severe respiratory failure, mechanical ventilation remains the main method of delivering oxygen and eliminating carbon dioxide. The method has many limitations and leads to both pulmonary morphological changes and physiological dysfunction [1, 2]. Low respiratory volumes and limited plateau pressure used as well as avoidance of cyclic opening and closing of pulmonary alveoli reduce
the adverse effects of mechanical ventilation, decreasing the risk of ventilator-induced lung injury (VILI), which was demonstrated in patients with acute respiratory distress syndrome (ARDS) [3, 4]. The first report demonstrating that the pulmonary alveoli should be opened and kept open throughout the respiratory cycle was published by Lachman in 1992. Thanks to his findings, the open-lung ventilation strategy and recruitment manoeuvres were introduced [5]. The studies using various techniques of lung recruitment in ARDS confirmed the beneficial effects of this procedure on blood oxygenation, yet the issues of shortened ventilation or reduced mortality are still disputable [6]. Considering the clinical importance of mechanical ventilation based on the open-lung strategy, special attention should be paid to assessment of the degree of lung aeration. Proper parameters of gas exchange in arterial blood gasometry may deceptively suggest adequate mechanical ventilation and lead to excessive ventilation of well aerated lung regions at the expense of worse aerated areas.

The aim of the present study is to discuss the modern methods of assessment of lung aeration as well as to show the advantages, disadvantages and possibilities of their use in clinical practice.

Computed tomography (CT) is the diagnostic examination that revolutionised the evaluation of morphological structures of individual lung areas. CT scanning uses X-rays to generate images of the internal organs. A series of scans is performed in one plane, which visualises many tissue layers of a given thickness. The computer-converted distribution of the linear X-ray attenuation coefficient (corresponding to the changes in tissue density within each layer) is expressed as a two-dimensional image [7]. The physical density of lungs is determined by measuring the absorption of radiation emitted by CT, expressed in Hounsfield units (HUs), which enables quantification of interstitial lung changes. Thanks to high resolution of the examination, heterogeneity of changes can be detected and their severity and nature determined (inflammatory and atelectatic changes, interstitial fibrosis, oedema).

The CT method described above has been used to assess lung expansion induced by recruitment manoeuvres [8]. In the study in patients treated due to ARDS,Gattinoni evaluated the effectiveness of recruitment manoeuvres and effects of various levels of positive end-expiratory pressure (PEEP) on the durability of improved gas exchange [2].

Although computed tomography provides accurate information concerning lung aeration, the method has several practical limitations. Critically ill patients have to be transported to the CT laboratory and the examination can’t be performed in a continuous mode due to exposure to high doses of radiation. Thus, the CT scan is not a dynamic image illustrating the changes in lung aeration during the entire respiratory cycle. Moreover, the quantification of lung aeration is complicated and to date has been used only for experimental purposes.

In everyday clinical practice, ultrasonography has been used for years. The method is widely applied for the diagnosis of ICU patients. In addition to numerous indications for US imaging, such as assessment of the myocardial function, confirmation or otherwise of the presence of fluid in pleural cavities, evaluation of kidneys and the urinary system, the US exam may also be useful for evaluation of lungs and diagnosis of their dysfunction. It is known that when there is air in the lungs, ultrasounds cannot penetrate the tissue as they are reflected and dispersed. Therefore, it would seem that US-assisted assessment of the properly aerated lung tissue is unfeasible, yet the method described is based on the analysis of ultrasonographic artefacts. In cases with decreased lung aeration caused by the presence of atelectatic areas or inflammatory consolidations, the tissue pattern is visualised during US scanning [10] (Fig. 1). This visualisation is accompanied by many characteristic ultrasonographic signs, thanks to which the causes of the existing pathology can be differentiated.

On the US scan of properly aerated lungs, horizontal artefacts (A lines) (Fig. 2), arising from the pleural line are visible as the multiple repetitions of this line at regular intervals. They can indicate both proper lung aeration and the presence of air in the pleural cavity. To differentiate them, the sliding phenomenon (the movement of the pulmonary pleura in relation to the parietal pleura) is used. In pneumothorax, the sliding phenomenon is absent, and the additional confirmation is the lung point i.e. the place on the thoracic wall where the US image of pneumothorax is replaced by the lung expanding during inspiration [11]. Increased water content in the lung tissue results in vertical artefacts (B lines) (Fig. 3), caused by reflection of ultrasounds from the fluid filling the interstitial space and/or pulmonary alveoli. The concentration of these lines defines the severity of interstitial oedema [12].

While discussing the clinical experiences with US assessment of lung pathologies, the study by Lichtenstein and co-workers is worth mentioning [13]. The authors compared the sensitivity and specificity of auscultation, radiography and US scanning of lungs in patients with ARDS and verified the diagnosis with chest CT. The findings were surprising. US examinations were diagnostically superior to lung auscultation and to bedside X-ray of the thorax. Depending on pathology, the diagnostic effectiveness of various methods varied; in cases with the presence of fluid in the pleura, the percentages were 61% for auscultation, 47% for X-ray and 93% for ultrasonography, whereas in cases of inflammatory and oedematous changes — 36–55%, 72–75% and 95–97%, respectively [13]. According to some other studies, in pneumothorax cases US examinations showed higher effective-
evaluation of antibiotic therapy efficacy and suggested that therapeutic decisions concerning changes of antibiotics could be based on US findings [15].

Furthermore, US examinations enable the evaluation of the effects of the mode of mechanical ventilation on lung aeration. Konstantinos and colleagues, who studied lung aeration in patients with ARDS using US imaging, showed that increases in PEEP from 5 to 15 cm H_2O led to increased aerated lung areas and correlated with improved arterial blood oxygenation [16].

The authors of the present paper recorded digitally US scanning during thoracic puncture in a patient with fluid in the pleural cavity. It was observed that evacuation of fluid was accompanied by subsidence of atelectasis of the lower lobe and improved lung aeration. This fact speaks strongly in favour of possible real time monitoring of the changes in lung aeration using the US technique.

The most recent technique used for the imaging of lung aeration is electrical impedance tomography (EIT). The bedside device Pulmovista 500 (Drager) enables observation of lung image changes depending on the respiratory cycle phase and degree of tissue aeration. The method relies on the fact that resistance of the lung tissue to an electrical impulse increases with its aeration. Sixteen pairs of electrodes placed on an elastic band fastened around the thorax measure the changes in thoracic tissue impedance in response to the electrical impulse emitted by two consecutive electrodes. Impulse emission is continuously moved around the thoracic cavity. The device performs 50 measurements per second, which in the respiratory cycle lasting 3 seconds generates 150 dynamically changing images. The intensification of aeration changes in a given lung region in a defined phase of respiratory cycle is expressed as different colours on a monitor. White colour denotes the largest changes in aeration of a particular lung area, while black colour is a non-ventilated region, in which aeration changes do not occur [17]. Compared to classical CT images, the EIT-generated scan is characterised by markedly lower spatial resolution. Such a picture is a visualization of changes in thoracic tissue impedance and does not provide information about the nature of morphological changes within the lungs. In this kind of imaging, a particular lung area of time-constant impedance will be presented in the same way on the monitor, irrespective of whether the lack of ventilation is caused by atelectasis, pleural fluid or pneumothorax [18]. Thanks to high time resolution, the changes are observed in real time. Moreover, the EIT monitor enables differentiation of improvement in total lung aeration resulting from the opening of atelectatic areas and from excessive extension of the properly ventilated lung regions.

The earlier studies on EIT carried out in animal models confirmed the repeatability of aeration results of various lung areas performed at various PEEP values [19]. Moreover,
the findings demonstrated the correlation between this method and CT results evaluating the recruitment of alveoli [20]. The use of EIT in patients treated due to acute lung injury enabled the adjustment of PEEP to provide mechanical ventilation without excessive inflation of some lung areas yet extending the atelectatic areas in other regions [21].

Pulmovista 500 is the first commercially available monitoring device based on the electrobioimpedance technique. However, due to relatively sparse clinical experience and high costs, its usefulness in everyday practice has not been sufficiently evaluated.

In contrast to the methods described above, still another method can be used to indirectly describe the sum of phenomena taking place in the lung. It is based on construction of a quasi-static pressure/volume (P/V) curve in the inspiratory and expiratory phase and describes the relations of airway pressure, volume and compliance according to the following formula:

\[ C = \frac{P}{V} \]

*C* — respiratory system compliance, *P* — gas pressure, *V* — gas volume

In the biological system, however, such simple relations never occur. The airway pressure during spontaneous breathing or mechanical ventilation is additionally affected by many external factors connected with the gas flow, airway resistance and pressure exerted by the respiratory muscles. Given so many variables, it is difficult to assess their interrelations. The construction of the P/V curve enables elimination of the effects of these additional factors. The generation of a fully static P/V curve requires complete stoppage of airway flow, which is unfeasible, as the patient has to be provided with continues gas exchange. Therefore, quasi-static curves are used, which are determined using the super syringe method (experimental method in which the patient has to be weaned from the ventilator) or the method of a very low gas flow. Based on the curves obtained — inspiratory and expiratory ones, hysteresis is determined, i.e. delays between these curves. Hysteresis is the phenomenon occurring in the closed system, involving the change of recordings of the process (i.e. the respiratory cycle) depending on its direction. On the graph of two dependent values, the phenomenon of hysteresis most commonly appears as a loop. If hysteresis is absent, the graph is a single curve arch. While plotting the P/V curve, the recording changes of the inspiratory and expiratory phase result from the delay in energy return by the respiratory system, visible on the graph as the difference in lung gas volume at the same airway pressure, depending on the respiratory phase [22].

According to Demory and colleagues, the value of hysteresis is a valuable indication for the purposefulness of recruitment manoeuvres. They determined hysteresis of the P/V curve in patients with ARDS. In patients with higher hysteresis, the possibilities of recruitability of the lung were higher, measured as an increase in volume at pressure peak during the recruitment manoeuvre [23] (Fig. 4).

Some ventilators available on the market enable the determination of the quasi-static P/V curve using a specially designed application, e.g. P/V Tool (Hamilton Medical, Switzerland). With its use, the recruitment manoeuvre can also be performed. This fully automated and repeatable application records the P/V curve using the linear pressure increase. To determine the P/V curve and perform the recruitment manoeuvre, spontaneous respiratory activity of the patient has to be stopped, which, unfortunately, requires relaxation or deep sedation [24]. For the recruitment procedure or determination of the P/V curve, the end pressure can be set, which is subsequently used by the ventilator as PEEP for further ventilation. A relevant asset of this method is the short time of the manoeuvre (up to 1 min), which minimally affects the patient’s hemodynamic parameters [25]. Moreover, the method enables repetition of the procedure when the respiratory system has been unsealed. The procedure is performed without weaning the patient from the ventilator whereas mechanical ventilation is continued immediately after its completion.

The method described above bases the assessment of lung aeration on the P/V curve, which reflects the sum of lung phenomena, without taking into account differences in aeration of their individual regions.

Amongst the presented methods, only lung CT has been recognised and accepted as the gold standard for assessment of lung aeration [1]. Considering all its limitation, a new optimal method is required. Such a new method, eliminating the drawbacks mentioned earlier, should offer possibilities of performing the examination without discontinuation of ventilation, and provide visualization of morphological changes in the affected lung areas in real time. US performed with standard devices seems to be the closest to the ideal method. However, its implementation requires theoretical knowledge and practical skills.

The remaining methods presented above fulfil the majority of criteria of the optimal method for assessment of lung aeration, yet have a relevant weakness. The measurement of P/V curve hysteresis is the result of pathology of the entire lungs and does not provide information on the location of lesions and their aetiology. Furthermore, only some ventilators are capable of determining the quasi-static P/V curve and performing the recruitment manoeuvre based on it.

The EIT monitor image is a visualization of changes in electrical properties of the thorax depending on the amont
of the air contained. Thanks to that, mechanical ventilation can be monitored, showing the aeration changes during the entire respiratory cycle depending on the mode of ventilation used. However, it should be remembered that impedance changes in the thorax may be caused by the factors other than interstitial lung pathologies and the monitor image does not reflect the morphological structure of the lungs.

As mentioned earlier, there are many methods of lung pathology imaging. Proper assessment of lung aeration during the therapy with mechanical ventilation seems to be helpful for therapeutic management. The particularly valuable methods enable quantitative and qualitative assessment of lung tissue aeration, location of pathological changes and determination of their aetiology.

References:

Figure 4. An example illustrating the recorded curve of pressure and volume from ZEEP (PEEP = 0 cm H2O) to 40 cm H2O (upper graphs) and the recruitment manoeuvre with 10-second interval at pressure peak, 40 cmH2O (lower graphs) in representative patients showing slight hysteresis (on the left) and high hysteresis (on the right) Hpv — P/V curve hysteresis, Vrm — volume increase during the recruitment manoeuvre (Courtesy of [23]).

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