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The mechanical properties of human ribs in young adult

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A good understanding of thoracic biomechanics is important for complete examination and control of chest behaviour under conditions of physiological and pathological work, and under the impact of external forces leading to traumatic loading of the chest. The purpose of the study was to analyse the mechanical properties of human ribs obtained from individuals under the age of 25 with scoliosis deformation and to correlate them with geometric properties of ribs.

Thirty three fragments of ribs (9th to 12th) were tested in three-point bending. Rib fragments were collected intraoperatively from female patients treated for scoliosis in the thoracic, thoracolumbar, and lumbar spine. The results were used to determine the maximum failure force, stiffness, and Young's modulus.

A significant relationship was found between the age and elastic modulus of the ribs. The analysis was carried out for two age groups, i.e., between the ages of 10 and 15 and between the ages of 16 and 22, and statistically significant differences were obtained for Young's modulus ($p = 0.0001$) amounting to, respectively, 2.79 ± 1.34 GPa for the first group and 7.44 ± 2.85 GPa for the second group. The results show a significant impact of age on the mechanical properties of ribs.

Key words: *rib, scoliosis, biomechanics, bending, strength*

1. Introduction

The thorax has a high mechanical resistance, especially resistance to injury, mainly due to distinctive elastic properties of the rib and spine system supported by muscles [1], [2].

Knowledge of thoracic biomechanics is important for complete examination and the understanding of chest behaviour under conditions of physiological work and under the impact of external forces in such cases as cardiopulmonary resuscitation or when determining the values of the forces leading to traumatic loading of the chest.

Assessments of the forces initiating rib damage, caused by the impact of dynamic external forces, are important in chest injuries incurred during car crashes. There is a constant increase in the number of car accidents, where thoracic injury constitutes the second most frequent type of injury (after injuries to the head) and may lead to fatal body injuries [4], [12]. On average, 30% of drivers (including 24% aged between 16 and 33) die due to chest injuries caused by head-on collisions of motor vehicles [21], [22]. Among children, most thorax injuries are blunt trauma, the vast majority of which are caused by car crashes with the highest mortality rate among adolescents, i.e., between the ages of 10 and 15 [32].

The location of ribs in the thorax regularly exposes them to the risk of impact of external forces. Despite numerous studies examining the processes occurring during the impact of dynamic external forces (as in the case of car crashes), there are relatively few studies analysing the mechanical properties under the conditions mimicking normal rib functioning.

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Studies analysing the mechanical properties of human ribs are undertaken by numerous authors who carry out three-point bending tests of whole ribs or rib parts [11], [16], [20], [30], [33], [36], [40]. At the same time analyses show the influence of the site of rib sampling (anterior, lateral or posterior) on the results obtained [11]. Research is also conducted into the mechanical properties of isolated cortical bone of ribs in the tensile test [19], [20], [33], and three-point bending [37].

Determination of mechanical properties of ribs is particularly important for scientific purposes, but even more so because of possible applications. The biomechanical analysis of the phenomena taking place in the thorax often uses the finite element method (FEM) [9], [17], [22]. Development of advanced numerical models of the thorax and simulation of the biomechanics of its operation require the supply of information on the strength of the ribs themselves, as well as the method of transfer of loads in the thorax [28], [29]. However, the material properties used for calculations and simulations of the phenomena connected with deformation are obtained from the data on physiologically correct ribs [10], [25].

Consequently, the accuracy of the obtained results of the numerical simulations depends strictly on the material parameters used in the model components. Experimental studies of the mechanical properties of ribs are conducted primarily on post-mortem material, obtained from people aged between 30 and 83 [11], [20], [36], [40]. Such analyses are typically performed for ribs from the 6th and 7th levels [16], [36], 7th and 8th levels [40] as well as 4th to 7th levels [20]. Only KEMPER et al. [19] and STITZEL et al. [37] used ribs from the whole thorax in their research; however, the main purpose of those studies was to determine the material parameters of isolated fragments of the cortical part of ribs.

Despite numerous works analysing mechanical properties of human ribs, there are no studies involving the rib material obtained from individuals under the age of 20. Therefore, the aim of this paper is to analyse the selected mechanical parameters of the human ribs obtained from young people and to correlate them with the geometric properties of ribs.

2. Methods

2.1. Specimens

A total of 33 ribs were collected intraoperatively from consecutive series of 17 female patients treated operatively for scoliosis in the thoracic spine with the posterior approach (4 individuals) and the thoracolumbar or lumbar spine with the anterior approach (13 individuals) – the table. The patients aged between 10 and 22. The Cobb angle of the major scoliosis curve ranged from 41 to 64 degrees (mean 52.7 ± 6.7). In the group examined, there were no systemic diseases affecting bone metabolism; the patients had not been treated with steroid drugs. Prior to surgical treatment, the patients did not use spinal braces. The specimens were obtained from the middle and posterior thorax, from the 9th to the 12th ribs (figure 1a).

Table. Data for rib specimens used in bending testing

Rib number	Number of ribs	Region
9	4	Posterior ($n = 3$) Lateral ($n = 1$)
10	8	Posterior ($n = 1$) Lateral ($n = 7$)
11	15	– Lateral ($n = 15$)
12	6	– Lateral ($n = 6$)

The material, in the form of rib fragments with an average length of 53 mm, was collected in accordance with the methodology described by SUK et al. [38]. Ribs were exposed subperiosteally; after resection of a particular segment the loose rib fragments were reconnected. Resected rib fragments were ground and used for posterior fusion, performed in patients after surgical treatment with the posterior approach. The segments of the ribs used in our tests were not employed for fusion. In the case of patients treated for scoliosis in the thoracolumbar or lumbar spine with the anterior approach, a single rib was removed, providing surgical access, and another rib might be removed from the ribs that caused chest deformities in patients with scoliosis. Resected rib fragments, as in the case described above, were used for anterior fusion, while the tests covered fragments not used for fusion.

Based on the assumption that cross-section of a rib is elliptical in shape, the external rib dimensions were measured (using electronic calliper with a measurement accuracy of 0.05 mm) in accordance with the directions of the long and short radii of the ellipse. The above parameters were measured in three places: at the point of planned application of the bending force and on the edges of the specimen examined (figure 1b).

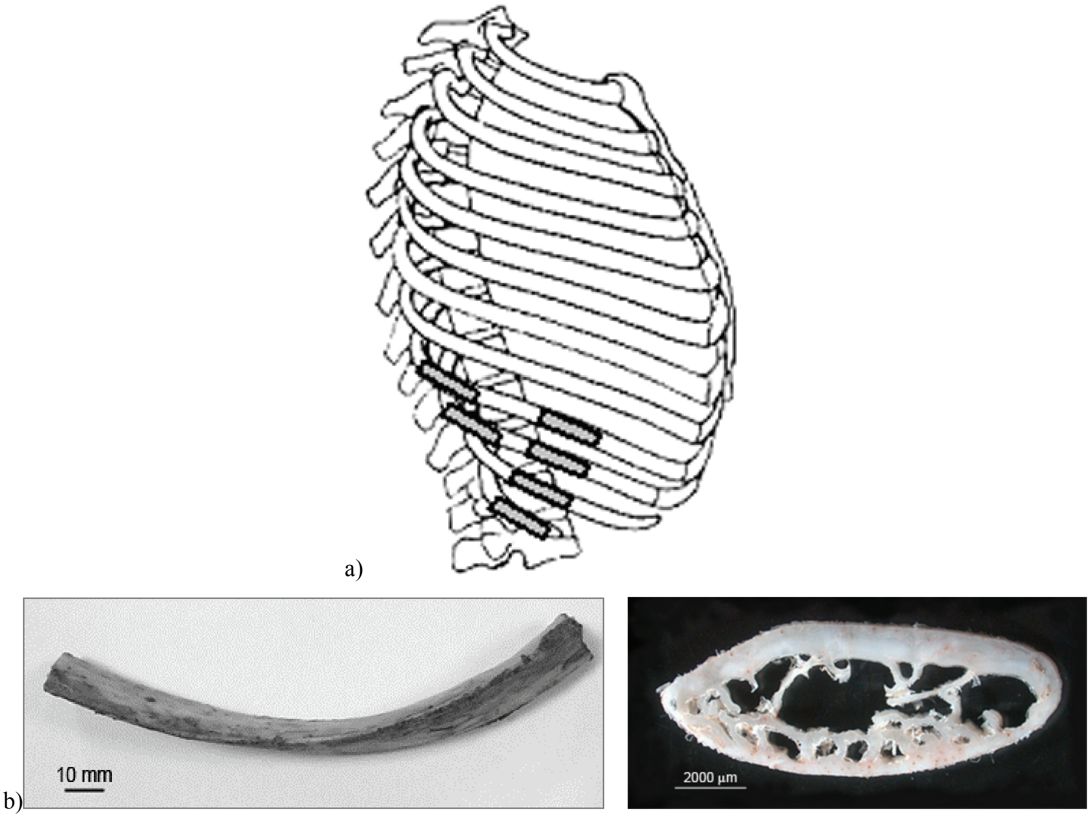

Fig. 1. Location of the rib specimens (posterior/lateral) (a),
example of rib and cross-section cut perpendicular to the rib near fracture (b)

The prepared material was stored until the day of the tests in double plastic packaging at a temperature of –20 °C.

2.2. Measuring setup

Mechanical properties were tested in three-point bending (figure 2), the application of force was focused in the direction simulating the bending force acting inside to outside of the thorax. Such a loading method simulated physiological work of ribs (i.e., mimicking of the forces resulting from the breathing function).

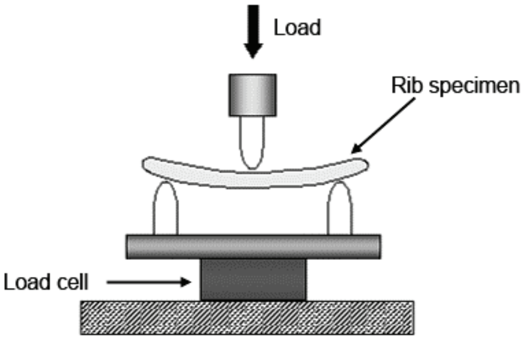

Fig. 2. Rib three-point bending test setup

The tests were carried out on the MTS MiniBionix 858 strength tester. The analysed rib fragment was subjected to a quasi-static bending load at a constant speed of 2 mm/min. In all cases, the test was continued until the moment of the specimen failure. During the tests, changes were recorded as the force F (N) versus displacement d (mm) of the rib in the direction of the bending force. The research results obtained were used to determine the maximum force and the bending moment, Young's modulus, and stiffness. Young's modulus was estimated on the basis of the following equation:

$$E = \frac{P \cdot L^3}{48\varDelta \cdot I}, \tag{1}$$

where:

P – failure force,
L – testing span,
$\varDelta$ – deflection,
I – moment of inertia.

The study assumed that the rib cross-section can be described by ellipse, and the rib is not solid, but contains cancellous bone with some kind of marrow inside. The ribs examined were cut in the transverse plane into 0.6-mm thick slices (figure 1b). Cross-sections of the ribs provided the basis for the measurement of the inner core thickness. The measurements were performed using a Zeiss stereomicroscope and AxioVision Rel. 4.8 software.

The moment of inertia was estimated with the use of slices from the middle part of the rib, approx. one cm away from the side of the failure location. The knowledge of the cortical part of rib enabled assessment of the moment of inertia by the treatment of rib as an ellipse of a known wall thickness.

2.3. Statistical analysis

Statistical analyses were performed based on the ultimate dependent variable force, ultimate moment, stiffness, and elastic modulus by using an analysis of variance (ANOVA) and a correlation analysis. Based on the ANOVA results, the tests using the *t*-test were performed to compare individual differences between means for datasets varying in age, rib geometry, and rib level. Significance was determined by a *p*-value of 0.05 or less and *r* value of 0.5 or greater.

2.4. Ethics

This study was approved by the Human Research Ethical Committee at the University of Medical Sciences. The patients' consent was obtained.

3. Results

The research revealed characteristics of force changes in relation to rib displacement. The research results obtained were used to determine the failure force $F_{\max}$ (the maximum force responsible for a significant drop in the measured force). Characteristics of the relationship between force and displacement allowed stiffness to be determined (figure 3). Stiffness was defined as the slope of the curve between two points on the force–dislocation curve, in the elastic range of loading (approximately 30% and 70% of the yield point). The maximum stiffness value was obtained for the 9th rib (302.30 ± 91 N/mm), and the lowest one for the 12th rib (95.30 ± 64.98 N/mm).

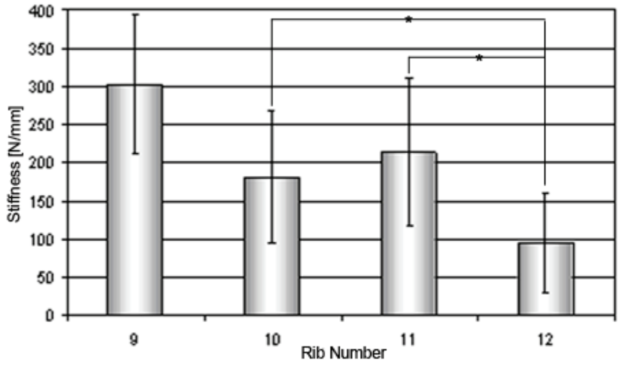

Fig. 3. Stiffness of ribs subjected to three-point bending. Vertical bars represent standard deviation from the mean

The maximum value of the force was the basis for calculating the maximum bending moment (figure 4). The highest values of the moment were obtained for the 10th and the 11th ribs, amounting to, respectively, 3.41 ± 2.18 Nm and 3.02 ± 1.98 Nm. The 12th rib was characterised by the lowest bending moment of 1.39 ± 0.60 Nm and, with respect to the 10th and the 11th ribs, it was a statistically significant difference ($p < 0.01$).

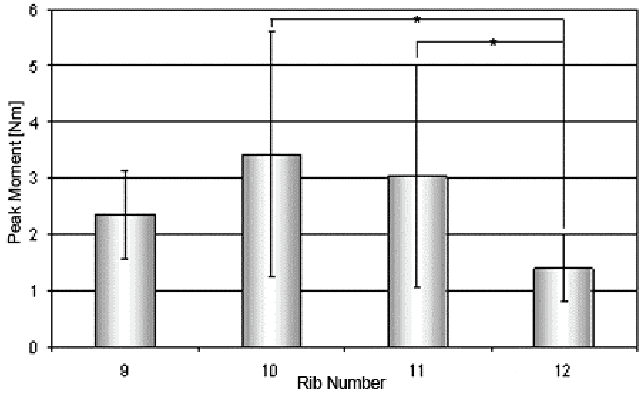

Fig. 4. Mean values of the maximum bending moment (* statistically significant differences, $p < 0.05$). Vertical bars represent standard deviation from the mean

Equation (1) was used to determine Young's modulus for individual ribs (figure 5a) and to assess the impact of age on that parameter (figure 5b). The maximum value of Young's modulus equals 5.97 ± 1.44 GPa for the 10th rib and is approx. 50% higher for the 12th rib – 3.05 ± 1.63 GPa ($p = 0.2$). The 11th rib is characterised by a small difference in Young's modulus, i.e., 5.67 ± 1.94 GPa, compared to the 10th rib. Young's modulus for the 9th rib equals 4.14 ± 1.65 GPa.

The relationship between the elastic modulus value and the age of the research material donated was analysed for two age groups, i.e., between the ages of 10 and 15 as well as 15 and 22, in accordance with the classification used by CERAN et al. [6]. The first group consisted of 16 rib fragments from 8 girls, the second group consisted of 17 fragments from 9 girls. Division of the research material revealed statistically significant differences in the values of Young's modulus ($p = 0.0001$) amounting to, respectively, 2.79 ± 1.34 GPa for the first group and 7.44 ± 2.85 GPa for the second group.

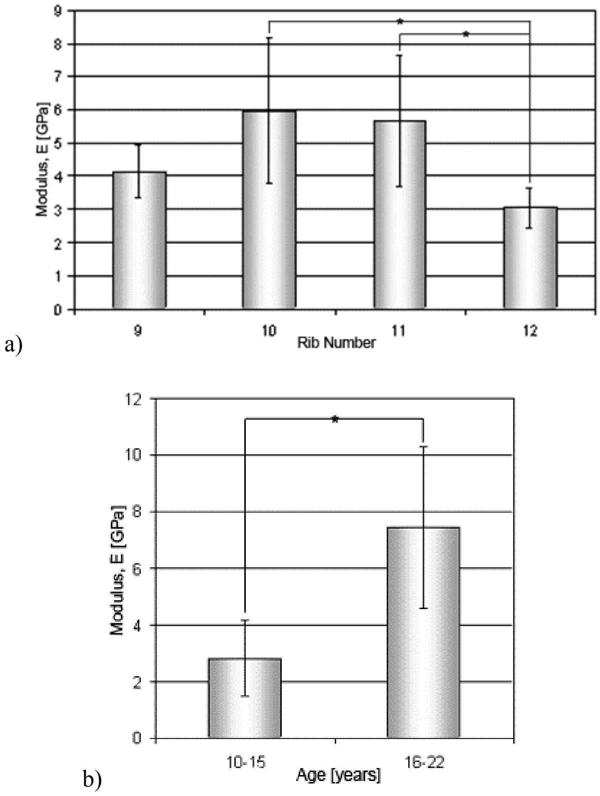

Fig. 5. Mean values of Young's modulus:
a) for individual ribs, b) depending on age
(* statistically significant differences, respectively, $p < 0.05$ and $p = 0.0001$).
Vertical bars represent standard deviation from the mean

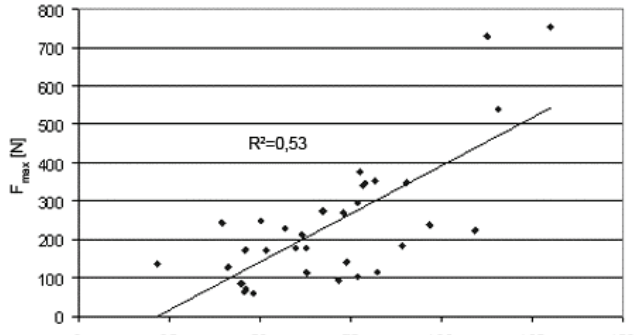

Fig. 6. Cross-section area of ribs at the point of loading versus the maximum failure force $F_{\max}$

Additionally, the impact of geometric properties of ribs at the point of loading on the maximum bending force was analysed (figure 6). The average value of the cross-section area of ribs amounts to 70.4 ± 24.4 mm^2 with the mean failure force of 249.9 ± 108.3 N, which corresponds to the mean bending moment of 2.73 ± 1.24 Nm. The Pearson correlation between the parameters is moderate ($r = 0.73$), but sufficient to confirm a statistically significant difference between the parameters examined.

4. Discussion

The present experimental analysis of the mechanical properties of ribs was carried out for the lower ribs of the human thorax. Of a special importance was the age of donors of the rib specimens used in research, i.e., between 10- and 22-year-olds, as well as the fact that the material was obtained intraoperatively. This material is unique and has not been used in any previous studies presented in the literature.

The primary mechanical parameters determined during three-point bending tests are as follows: the maximum bending moment, Young's modulus, and stiffness. As a result of bending ribs from the level 4–7 (individuals aged between 42 and 81), KEMPER et al. [20] obtained Young's modulus of 18.9 GPa for the anterior part of the ribs and 21.1 GPA for the lateral part. The above value is significantly higher than the values obtained in this study, i.e., an average of 4.71 ± 1.67 GPa. The elastic modulus values estimated in this paper are closer to the values reported by YOGANANDAN and PINTAR [40], who, while examining the 7th and the 8th ribs, determined Young's modulus at a level of 2.08 ± 0.45 GPa. Those studies were carried out on a sample of 120 post-mortem specimens obtained from individuals aged between 29 and 81. Under similar conditions of test execution, STEIN and GRANIK [39], SANDOZ et al. [33], and CHARPAIL et al. [7] obtained the modulus of elasticity of about 11 GPa.

On the other hand, the bending moment obtained in the study as well as the stiffness resemble the data in the literature [40], [7], [20] and amount to, correspondingly, 25 Nm and 190 N/mm.

A comparison of the values of Young's modulus should take into account factors which can influence the results, i.e., the level of the rib examined and the collection point (anterior, lateral), the age of the material donor, and the loading speed.

Most of the analyses involve post-mortem material of ribs coming from individuals aged between 30 and 80 [20], [35]–[37]. Studies carried out by many authors [3], [34] point to a significant impact of age on the mechanical properties of bones. Bone mineralization, particularly in the cortical part, increases with age, whereas collagen matrix cohesion decreases.

Since collagen matrix significantly affects the elastic properties of bones [34], its diminishing volume decreases load resistance of bones [41]. This process causes significant differences in both mechanism and forces leading to thorax damage and rib fractures in patients from different age groups. Among people over the age of 60, rib fractures occur often due to low trauma [18]. What is very important, according to the analysis carried out by FLAGEL et al. [15], fracture of many ribs, i.e., 6 or more, significantly increases the risk of death. In young people, the most common cause of chest injuries and rib fractures are road accidents which result in additional internal injuries, including: pneumothorax, hemothorax, vertebral trauma, and diaphragmatic injury [24], [32], [35]. A regards chest injuries in children, it must be noted that, in accordance with CERAN et al. [6], they occur more frequently in boys, which is also confirmed by SAMARASEKER et al. [32]. Unlike the aftermath of the injuries reported in adults, in the case of children, flail chest is uncommon, and only rarely requires surgical treatment [6]. Despite the large energy connected with transport accidents, the mortality rate in this age group is also low. Based on the analysis of material covering 225 patients treated for chest trauma, CERAN et al. [6] did not report any deaths. The differences between the mechanical properties of children and adult bones, highlighted in clinical trials [6], are consistent with the results of experimental studies conducted by CURREY and BUTLER [13], who showed differences in the mechanical properties (including Young's modulus, bending strength, and dissipation energy) of the femoral bone obtained from children, youths, and adults (aged between 2 and 48). The values of the elastic modulus changed significantly between the age group of 2–6-year-olds and the group of 6–14-year-olds.

In the age group of 16 to 48-year-olds, the values of the modulus increased but the rate of that growth as well as the differences in the values obtained were lower than in the case of younger age groups.

The results of the research presented in this paper fully confirm the observations made by CURREY and BUTLER [13]. In the group of specimens representing the age range of 10–15 years, the values were over 50% lower than in the age range of 16–22 years. It also provides an important justification of the differences in the values of Young's modulus presented in [13], compared to the values presented by other researchers [7], [20], [33], [36].

Another factor affecting the research results is the loading speed. The majority of studies on the mechanical properties of ribs use large loading speeds (100–500 mm/s) [7], [11], [19], [20]. These boundary conditions in the rib tests create quasi-dynamic conditions, which simulate circumstances similar to a car crash. Bone tissue shows viscoelastic properties, and the loading speed has a large impact on the results obtained [39], [5]. Generally speaking, an increase in loading speed is accompanied by an increase in maximum tension and Young's modulus, whereas strain decreases.

The loading speed used in the above study can be regarded as quasi-static (0.033 mm/s), which, considering the speeds used, among others, by KEMPER et al. [20] (172 mm/s), constitutes another element explaining the differences in the obtained values of the elastic modulus.

The study has several limitations. One of the simplifications made is the adoption of identical mechanical properties along the entire rib length, whereas, due to irregular cross-sectional geometry and curvature, there exist regional differences in bone mechanical properties. The completed tests simulated the application of the force concentrated from the inside to the outside of the thorax, which mimics the physiological work of the ribs. On the other hand, injuries, including rib fractures, occur under the impact of external forces, whose orientation is the opposite of the loading force scheme used in the present study. The thorax is adapted to transfer loads mainly from inside to outside, therefore, we can assume that the application of such a loading model can affect the values obtained. However, the "physiological" model is used in the majority of studies analysing material parameters of ribs in the three-point bending test [11], [26], [20], [40].

One of the limitations of the present research is the fact that it analyses the ribs coming from patients treated for idiopathic scoliosis. Some data testify to an increased risk of osteoporosis in scoliotic patients during adolescence, irrespective of the treatment method used, including brace treatment [8], [23]. Although some of the research is based on the evaluation of a small group of patients or indicates the need for further long-term prospective studies, we should be cautious of extrapolating the obtained results to the healthy population [23], [31]. Another limitation, which could affect the results obtained, is a deforming impact of scoliosis on the fragments of the removed ribs. It should, however, be noted that in the material analysed there are no patients with large Cobb angle scoliosis and, furthermore, according to reports by ERKULA et al. [14], there is no correlation between the Cobb angle, the spinal rotation, and the degree of rib deformity.

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