

VARIATIONS IN DIMENSIONS AND SHAPE OF THORACIC CAGE WITH AGING: AN ANATOMICAL REVIEW

ALLWYN JOSHUA, LATHIKA SHETTY, VIDYASHAMBHAVA PARE

Correspondence author: S.Allwyn Joshua, Department of Anatomy, KVG Medical College, Sullia-574327 DK, Karnataka, India. Email: oxfordjosh@yahoo.com. Phone number; 09986380713. Fax number – 08257233408

ABSTRACT

The thoracic cage variations in dimensions and proportions are influenced by age, sex and race. The objective of the present review was to describe the *age related changes* occurring in thoracic wall and its influence on the pattern of respiration in infants, adult and elderly. We had systematically reviewed, compared and analysed many original and review articles related to aging changes in chest wall images and with the aid of radiological findings recorded in a span of four years. We have concluded that alterations in the geometric dimensions of thoracic wall, change in the pattern and mechanism of respiration are influenced not only due to change in the inclination of the rib, curvature of the vertebral column even the *position of the sternum* plays a pivotal role. Awareness of basic anatomical changes in thoracic wall and respiratory physiology with aging would help clinicians in better understanding, interpretation and to differentiate between normal aging and chest wall deformation.

Key words: Thoracic wall; Respiration; Ribs; Sternum; vertebral column

INTRODUCTION

The thoracic skeleton is an osteocartilaginous frame around the principal organs of respiration and circulation. It is narrow above and broad below, flattened antero-posteriorly and longer behind (Datta 1994). Thoracic variation in dimensions and proportions are partly individual and also linked to age, sex and race (Williams, 2000). Although it is known that rib cage geometry changes from early infancy to adulthood, the timing of this change has not been described (Openshaw et al., 1984).

Respiration is a complex activity that involves contraction of respiratory muscles and movement of the rib cage to provide the required lung volume during inspiration. The rib cage displacement is based on an increase in its transverse and anteroposterior dimensions, together or separately (Luttgens et al., 1992).

Analysis of the lung volume displacement during respiration entails studying body wall movement during respiration. Three mechanisms of the body wall movement during respiration are: rib cage expansion and contraction, anterior abdominal wall expansion or contraction and spine flexion-extension. Although spine movement can cause substantial displacement of the chest wall, it does not contribute significantly to the changes in lung volume (Smith et al., 1986). The degree to which rib cage and abdominal wall movements contribute to the lung volume displacement during respiration depends on the body anatomy, body posture and breathing condition. The contribution of the rib

cage movement to the volume displacement of the lungs was evaluated by (Agostoni et al., 1965; Grimby et al., 1968; Loring, 1982) for various human body postures. It should be noted that rib cage displacement not only contributes directly to the volume displacement of the lung, but also facilitates the movement of abdominal viscera and the primary act of the diaphragm i.e. as the rib cage expands, it lowers abdominal pressure and thus permits a larger fraction of trans-diaphragmatic pressure to go into lowering the pleural pressure (Mead, 1995)

Most of the age-related functional changes in the respiratory system result from three physiologic events: progressive decrease in compliance of the chest wall, in static elastic recoil of the lung and in strength of respiratory muscles (Jean-Paul, 2005). Present reviews explore age-related anatomical changes in the thoracic cage and their consequences in respiratory mechanics. However, there is very limited data in the literature on the age related changes in pediatric thorax geometry, on the positional and aging changes of sternum. The present review would be first of its kind in an attempt to include not only the rib and vertebral column but also the sternum as a key component in framing thoracic shape and dimension. Therefore radiological findings in the present review are directed towards three major structures involving three different age groups (infants, adults and elderly) 1. Change in the inclination of ribs; 2. Change in the curvature of vertebral column; 3. Change in the position of the sternum.

Thoracic cage evaluation through Imaging

Clinical evaluation of the thorax is performed using a variety of imaging techniques such as chest radiography (CXR), Computer tomography (CT), Magnetic Resonance Imaging (MRI) (Wehrli et al., 2007; Well et al., 2007) Three dimensional (3D) reconstructed CT images from the axial datasets may prove useful (Alkadhi 2004) in examining the three dimensional geometry of the thoracic cage. Present article has utilized CT plain and reconstructed images of thorax, sagittal view of thorax has been used to study the structures as it provides better exposure of sternum and vertebral column in comparison to lateral chest X ray images. Axial section of thorax at xiphisternal level has been used in the present review article to study the shape of thoracic cage with aging. Many authors have previously used CT axial images to calculate thoracic index and radiological indices of chest by dividing the anteroposterior diameter by the lateral diameter at three thoracic levels namely, the manubriosternal junction, the diaphragmatic dome, and midway between these two reference levels (Kangaroo, 1988; Howatt, 1965; Meredith 2007; Scammon 1927; Takahshi 1966).

Many authors like Chang et al. performed 3D reconstructions of multislice CT images in pediatric subjects following Ravitch thoracoplasty, and quantified the volume of ossification in the costal cartilage by the removal of the bony thoracic cage at proper software window settings (Chang et al. 2007) which has provided a basis to understand the growth pattern of ribs in the present review. Additional information concerning the changes in the rib cage dimensions, the shape and cross-sectional geometry of the ribs and the chest wall thickness has been comprehensively collected from Mohr et al., 2007; Takahashi, 1955; Givens et al., 2004; Yoganandan, 1988.

Mohr et al. reported detailed rib biometrics for adults such as the apparent rib curvature, longitudinal twist along the diaphysis, unrolled curvature of the outer cortical surface, cross-sectional geometry (height and width) of the ribs along their length, cortical thickness and area of the cortical and medullary canal (Mohr et al., 2007)

Age related changes of the sternum:

The human sternum consists of cranial manubrium (prosternum), an intermediate body or mesosternum and caudal xiphoid process (metasternum). In adults its total length is about 17 cms, less in females (Jit, 1984) In addition to the three major sections, the mesosternum in early life consists of four sternabrae, which from the costal relations appear to be intersegmental. The sternum as a whole descends with respect to

spine from birth up until age 2 to 3 years, causing the ribs to angle downward when viewed laterally, and the shaft of the rib to show signs of axial twist deformation (Scheuer, 2000).

There has been very limited literature explaining the modifications of the sternal position in relation to aging. The present section of the review has summarised the positional variations of the manubrium and body of sternum especially from infancy to elderly and also its influence on the chest wall shape. To begin with infants, the un-ossified mesosternum (Body of the sternum) comprising three or four sternabrae, the first and second sternabrae are aligned in the same plane as the manubrium making the sternal angle less prominent (Fig 1A) and the third and the fourth sternabrae if present curves inwards towards the xiphisternal end, making the chest wall contour convex forwards, sometimes gives a false appearance of pectus carinatum (Pigeon chest) (Fig 2).

At around puberty, the union between the sternal centres begins and proceeds from below upwards, such that by 25 all are united. Fusions of all four sternabrae makes the body of sternum a single unit and produces an angulation between manubrium and the first sternabrae at manubriosternal joint making the sternal angle more prominent (Fig 1B). With the fused sternabrae and also fused manubriosternal and xiphisternal junction (Bruno et al., 2012; Estenne, 1985), the convexity of the body of sternum reduces and the chest wall appears more flattened in antero-posterior aspect (Williams, 2000). With advancing age, we have observed that the lower end of sternum curves inwards making the upper part of the body and manubrium protrude anteriorly, with prominent convexity forwards when compared to infants (Fig 1C). Position and morphological variation in shape and structure of sternum with advancing age may not be the sole reason for the change in the contour of chest wall but surely participates along with other key structures like vertebral column, ribs and costal cartilages in modifying the chest wall shape.

Changes occurring in the vertebral column with aging:

Ossification of the cartilaginous vertebra commences as early as seventh week. Typically a vertebra is ossified from three primary centres and five secondary centres. The primary centre appears between the seventh and eighth; one centre for the centrum, and one centre for each neural arch. At about puberty five secondary ossification centres appear – one for the spine, one for each transverse process, and two for ring epiphyseal centres for the upper and lower

surfaces of the centrum. Vertebral column growth is due to the summation of growth of individual vertebrae; the length of the spine being a major component of overall stature. At birth the ossified component of the vertebra has same height as the intervertebral cartilaginous component (Brander, 1970)

In infants, the vertebra body growth is incomplete which is evident in the anterior and posterior margin of the vertebral body and wide intervertebral space in the thoracic column are indicative of ongoing process of ossification, can be one of the reasons for shallow kyphotic curvature in thoracic spine (fig 1A).

When compared with adults the vertebral column shows prominent primary and secondary curvature. This change is seen due to increased posterior depth of vertebral bodies in thoracic vertebra and more prominent paravertebral musculature (Fig 1B). Growth in the height occurs at the upper end after puberty and can be indentified in subjects in mid-twenties (Bernick, 1982) Adolescent growth spurt can occur between 13 and 15 years in males and 9 and 13 in females (Taylor et al., 1983) The thoracic curve is concave forwards; it extends between second and eleventh thoracic vertebrae with its apex lying between sixth and ninth thoracic vertebrae.

In old age, degenerative changes occurring in the vertebral body seen as lipping and osteophyte formation (fig 1C). Reduced height of vertebral bodies, degenerating intervertebral disc, reduced intervertebral spaces and adaptive posture are few of the cumulative reasons for exaggerated kyphotic curvature in elderly (Williams, 2000).

Changes occurring in the ribs with age:

In infants the rib length is shorter in comparison to adults mainly due to incomplete ossification. Ribs in children show a smooth outward curvature with the angle of the rib being less prominent. Sternal ends of the ribs especially the vertebro-sternal ones appear at the same level its vertebral end and are placed more horizontally (Fig 3A). All these factors minimise the participation of intercostal muscles there by limiting the contribution of upper rib cage during respiration (pump handle movement). This explains the abdominal pattern of respiration in children. As age advances the rib ossification is complete, length of the ribs increases, and the costal cartilages are well defined. With the increased growth and height of vertebral body the ribs are placed more obliquely, making the sternal end lower than the vertebral end, which favours the expansion of anterior thoracic wall with movement of body of sternum (pump handle movement). The pattern of respiration then

becomes abdomino-thoracic assisting in pump handle and bucket movements of rib cage (Fig 3B).

In old age due to decreased height of the vertebral column, ribs change to a more horizontal position. Thoracic cage becomes rigid due to calcified costal cartilages (Vaziri et al., 2009) and fused manubriosternal joint (Fig 3C), which again alters the pattern of respiration and also reduces chest expansion.

Many methods have described in the literature about measurement of rib inclination. Among those, is the method adapted by Kent et al describing the Lateral Rib Angle—as the angle made by a line connecting the point at 0% (tubercle) and at 100% (costochondral junction) projected onto the sagittal plane and the z-axis (vertical). A greater angle indicates a more horizontal rib (Kent et al., 2005). Another method by Openshaw et al with a clear celluloid film placed over each radiograph and the following points were marked: the most lateral points of ribs 1-10; the necks of ribs 1-10; the centres of each vertebral body; the dome of each diaphragm; the position of the clavicles. For each film a "slope index" was calculated for each rib pair (Openshaw et al., 1984)

We have devised a new method in measuring the rib inclination especially confined to vertebra-sternal ribs (1st -7th rib) ; inclination of the second rib can be assessed by measuring the angle produced at the manubriosternal joint (sternal angle) by joining the line from the space between lower demifacet of first thoracic and upper costal demi-facet of second thoracic vertebra to the manubrio-sternal joint and with the horizontal line passing from manubrio-sternal joint to fourth thoracic vertebra (Fig 4). Lesser angulation indicates horizontally placed rib as in infants and elderly, the greater the angle more is the inclination as seen in adults (Fig 5).

Changes in the shape of the thoracic cage:

Openshaw et al. (1984) analyzed chest radiographs (from 38 individuals aged 1 month to 31 years) and CT scans (from 28 individuals aged 3 months to 18 years) and reported that infants and very young children (<2 years) have more horizontal rib angles and higher sternal clavicular heads and diaphragmatic domes than older children and adults. Also, the cross sectional chest shape was observed to change from the rounded infantile form to the more ovoid adult form by the age two years. This age-related shape change was quantified by Dean et al using the Thoracic Index (TI); defined as the ratio of the antero-posterior diameter of the chest to its lateral diameter. If the value of TI is closer to one, it indicates a circular cross-section, while a value closer to zero indicates

an oval cross-section (Davenport, 1934; Dean et al., 1987).

In infants the shape of the thoracic wall appears oval or heart shaped in CT axial section image (Fig 6A). This shape of the chest wall is primarily due to shorter rib length, contributed by forward projection of sternum and finally the proximity of the vertebral body to the sternum, reducing the sterno-vertebral distance. In adults, as the rib length increases so does the sterno-vertebral distance and chest assumes reniform shape (Fig 6B). Finally in old age the thoracic wall is almost rounded in shape mainly due to exaggerated kyphotic curvature and forward projection of sternum (Fig 6C) [Edge et al. 1964].

Another possible explanation is that changes in posture may lead to changes in chest wall shape. In support of this suggestion Krahl, (1964) cites the case of a congenitally bipedal goat which developed an upright posture. A normal goat's chest is flattened laterally but this goat developed a chest wider than it was deep, similar to that of a human adult. The timing of the changes in rib slope and the height of the clavicles and diaphragm suggests that posture has an important influence on thoracic shape. These rapid changes from birth to 2 years occur just at the time when the upright posture is being adopted and when the weight of the lungs and abdominal contents could affect the configuration of the thorax. With time, the gravitational forces operating on the rib cage together with the effects of rib growth would be expected to result in the observed changes.

Whatever the reason for the changes in thoracic shape the very young child would appear to have less potential for thoracic expansion than the older child and adult because of the instability of the thoracic cage and the lower efficiency of the diaphragm (Muller, 1979). Not only is the rib cage more pliable in the very young, but the ribs also appearing to be more horizontal than in the adult (Engel, 1974; Meinert, 1901; Howard, 1949). The pliable rib cage allows the chest wall to move

inwards during strong diaphragmatic contraction, while the more horizontal lie of the ribs is likely to limit the potential for thoracic expansion by rib cage movement in the cephalic direction. Possibly this relative mechanical inefficiency of the rib cage contributes to the frequency of respiratory problems in young children. Respiratory muscle performance is impaired concomitantly by the age-related geometric modifications of the rib cage (Perez et al., 1996), decreased chest-wall compliance, and increase in functional residual capacity (FRC) resulting from decreased elastic recoil of the lung (Turner, 1968). Kyphotic curvature of the spine and the antero-posterior diameter of the chest increase with aging, thereby decreasing the curvature of the diaphragm and thus its force-generating capacity (Edge et al., 1964). Changes in chest wall compliance lead to a greater contribution to breathing from the diaphragm and abdominal muscles and a lesser contribution from thoracic muscles. The age-related reduction in chest-wall compliance is somewhat greater than the increase in lung compliance; thus, compliance of the respiratory system is 20% less in a 60-year-old subject compared with a 20-year-old.

Estenne and colleagues measured age-related changes in chest wall compliance in 50 healthy subjects ages 24 to 75: aging was associated with a significant decrease (31%) in chest wall compliance, involving rib cage (upper thorax) compliance and compliance of the diaphragm-abdomen compartment (lower thorax). Calcification of the costal cartilages and chondrosternal junctions and degenerative joint disease of the dorsal spine are common radiologic observations in older subjects and contribute to chest wall stiffening (Edge et al., 1964). Changes in the shape of the thorax modify chest wall mechanics; age related osteoporosis results in partial (wedge) or complete (crush) vertebral fractures, leading to increased dorsal kyphosis and antero-posterior diameter (barrel chest).

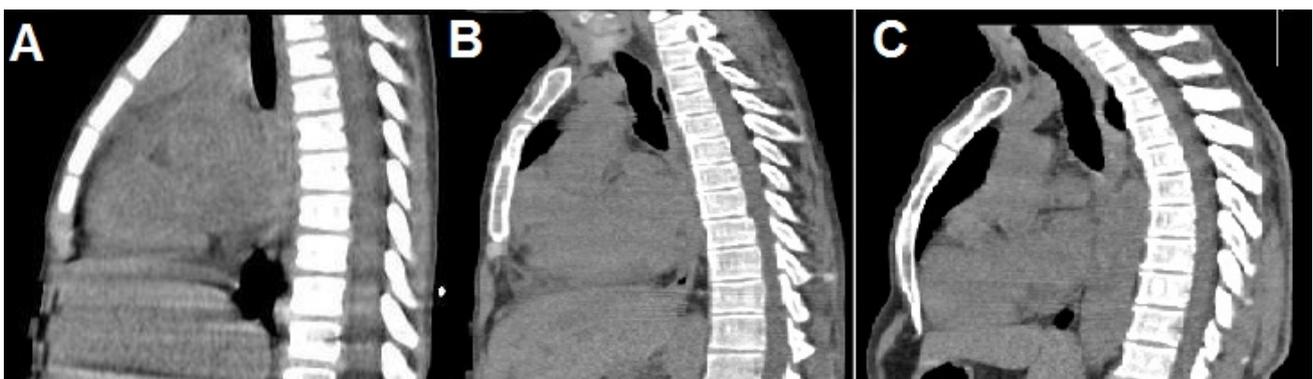


Figure 1: CT non contrast images, sagittal section showing Sternal position and angulation at manubriosternal joint and stages of thoracic kyphosis of three age groups. A-Infants, B- adults, C-elderly

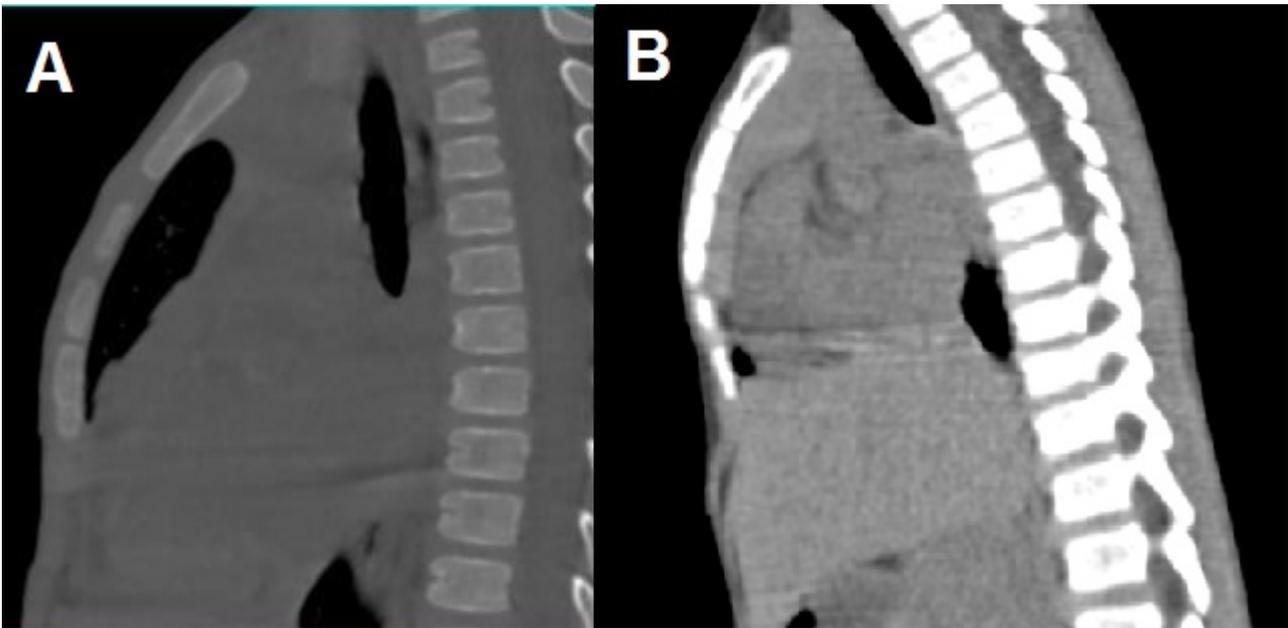


Figure 2: CT 3-D bone reconstructed images of thorax, showing the similarities between normal chest and pectus carinatum

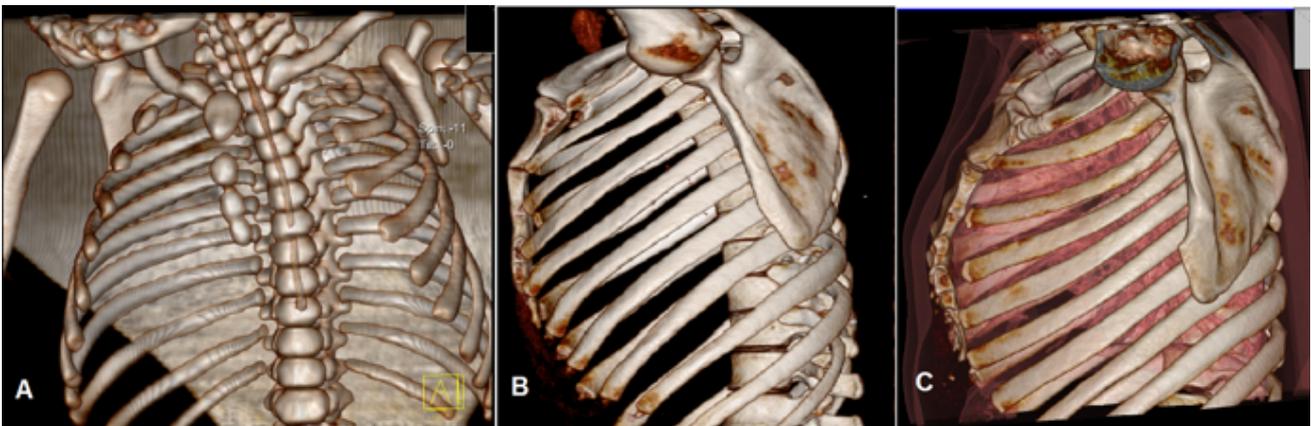


Figure 3: CT 3-D bone reconstructed images of thorax, showing the rib inclination in different age groups. A- Infants, B- adults, C-elderly

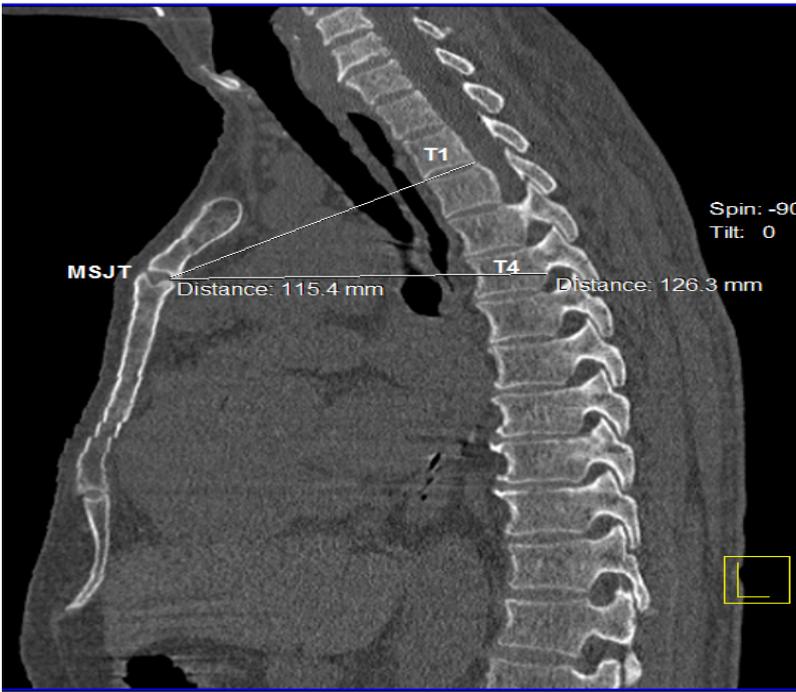


Figure 4: CT image, sagittal section, depicting the measurement of second rib inclination at manubriosternal joint (T – thoracic vertebra, MSJT – manubriosternal joint)

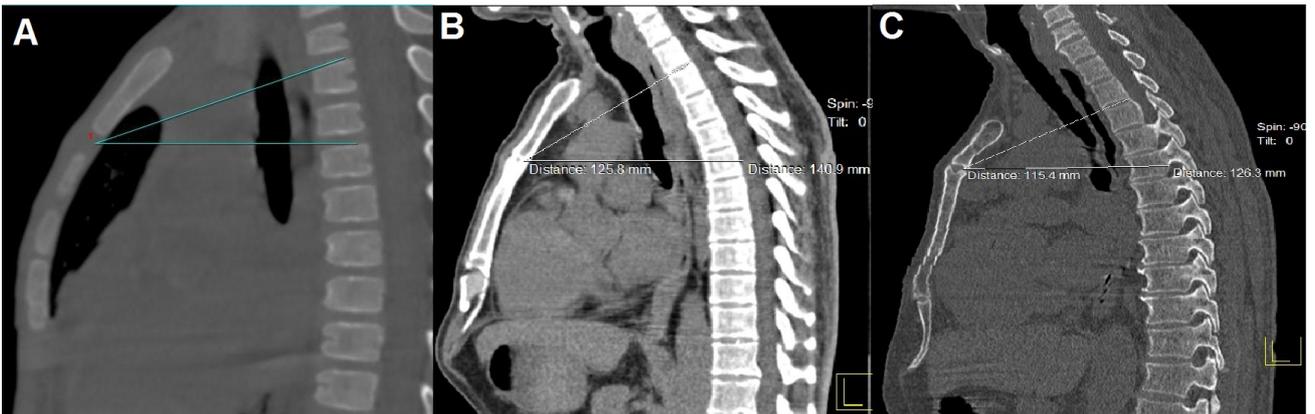
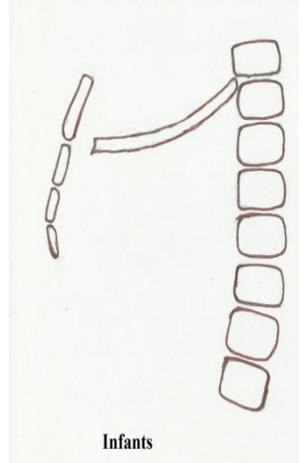
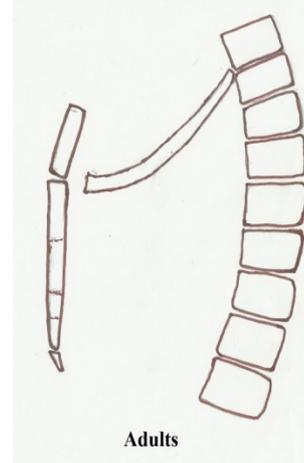
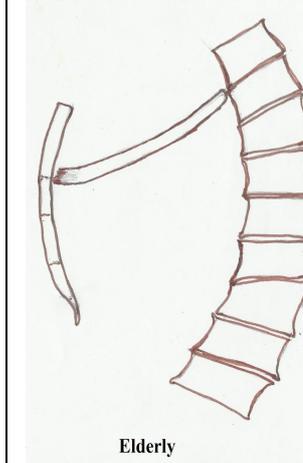


Figure 5: CT image, sagittal section, showing the angle produced by second rib inclination at manubriosternal joint at different age groups. A-Infants, B- adults, C-elderly



Figure 6: CT axial section of thorax, showing the internal thoracic dimensions and shape at different age groups. A-Infants, B- adults, C-elderly

Table 1: Summarizes the important changes in the key components of the thoracic wall in three age groups

	Components	In infants	Adults	Elderly
1	Sternum	Unossified sternebrae	Forms a single segment	Lower end curves inwards
2	Manubriosternal angulation	Less prominent	Prominent	Fused and more prominent
3	Vertebral column	Shallow kyphotic curvature	Well developed kyphotic curvature	Exaggerated kyphotic curvature
4	Ribs (vertebra-sternal ribs)	Horizontally placed	Obliquely placed	More horizontally placed
5	Thoracic cage as whole	Oval shaped	Reniform	Barrel shaped
6	Images			

Breathing pattern

Breathing pattern and thoraco-abdominal motion may be influenced by several factors, such as the individual’s positioning (Britto et al., 2005; Maynard, 2000) age, sex respiratory overload, neuromuscular diseases, lung diseases associated with increased airway resistance (Allen et al., 1990; Rusconi et al., 1995). Each component of the thoracic wall contributes to the pattern of respiration with ribs playing a vital role.

Each rib has its range and direction of movement contributing to thoracic respiratory excursions. Each acts like a lever, its fulcrum immediately lateral to costo-transverse articulation; hence when shaft is elevated, the neck is depressed and vice versa. Slight movement in the vertebral end of rib is magnified at the sternal end. First and second rib moves little except in deep inspiration and usually associated with movement of manubrium. Third to sixth rib thrusts the anterior end forwards; this also moves the body of sternum

similarly at manubriosternal joint leading to increase in the antero-posterior thoracic diameter.

Pattern of respiration in infants being predominantly abdominal mainly influenced by horizontal position of ribs, which reduces the participation of intercostal muscles there by limiting the contribution of upper rib cage and during respiration (pump handle movement) which explains the abdominal pattern of respiration in children. As age advances the length of the ribs increases and the costal cartilages are well defined. With the increased growth and height of vertebral body the ribs are placed more obliquely, making the sternal end lower than the vertebral end, which favours the expansion of anterior thoracic wall with movement of body of sternum (pump handle movement) and the pattern of respiration becomes abdomino-thoracic assisting in pump handle and bucket movements of rib cage and thoracic expansion in synchrony with the abdominal expansion.

Veronica et al described the breathing pattern in elderly participants presenting significantly greater inspiratory phase relation and expiratory phase relation than the participants aged 20 to 39. The presence of greater thoraco-abdominal asynchrony observed among the elderly participants may have been due to structural modifications to the rib cage, weakness of the respiratory muscles, and changes to the respiratory drive (Jassens, 1996; Muiesan, 1971) given that these factors may increase respiratory overload (Alves et al., 2008; Pierce et al., 1976). Main changes relating to the rib cage are its reduction in compliance. Among healthy individuals, these changes are more evident after the age of 80. The breathing pattern is influenced by sex whereas the thoraco-abdominal motion is influenced by age (Veronica, 2010; Richards, 1961).

To conclude, this review has analysed and focussed on key structural and morphological changes of important anatomical components involved in the frame work of thoracic wall. Alterations in the geometric dimensions and shape of thoracic wall, change in the pattern and the mechanism of respiration are influenced not only due to change in the inclination of the rib and the curvature of the vertebral column even the position of the sternum plays a pivotal role. Awareness of basic anatomical changes in thoracic wall and respiratory physiology with aging would help clinicians in better understanding, interpretation and to differentiate between normal aging and chest wall deformation.

Conflict of interest: None

Sources of funding: self

REFERENCES

1. Alkadhi H, Wildermuth S, Marincek B, Boehm T. 2004. Accuracy and Time Efficiency for the Detection of Thoracic Cage Fractures: Volume Rendering Compared With Transverse Computed Tomography Images. *Journal of Computer Assisted Tomography* 28(3):378-385
2. Allen J, Wolfson M, McDowell K, Shaffer T. 1990. Thoracoabdominal asynchrony in infants with airflow obstruction. *Am Rev Respir Dis* 141(2):337-42.
3. Alves G, Britto R, Campos F, Vilaça A, Moraes K, Parreira V. 2008. Breathing pattern and thoracoabdominal motion during exercise in chronic obstructive pulmonary disease. *Braz J Med Biol Res* 41(11):945-50.
4. Agostoni A, Mognoni P, Torri G, Saracino F. 1965. Relation Between changes of rib cage circumference and lung volume. *J Appl Physiol.* 20:1179–1186
5. Bernick S, Cailliet R. 1982. Vertebral end-plate changes with aging of the human vertebra. *Spine* 7:97-102
6. Britto R, Vieira D, Rodrigues J, Prado L, Parreira V. 2005. Comparison of respiratory movements in adults and elderly. *Rev Bras Fisioter* 9(3):281-7.
7. Bruno H, Gustavo P, Klaus I, Gláucia Z, Eduardo G, José M, Edson M. 2012. The chest and aging: radiological findings. *J Bras Pneumol* 38(5):656-665
8. Chang P, Lai Y, Chen C, Wang J. 2007. Quantitative evaluation of bone and cartilage changes after the Ravitch throacoplasty by multislice computed tomography with 3-dimensional reconstruction. *Journal of Thoracic and Cardiovascular Surgery* 134(5): 1279-1283.
9. Datta AK. 1994. Essentials of human anatomy. Thorax and abdomen. 3rd edn. Current Books International, Calcutta, pp 80–86.
10. Davenport CB. 1934. Thoracic index. *Hum Biol* 6: 1-8.
11. Dean J, Koehler R, Schleien C, Michael J, Chantarojanasiri T, Rogers M, Traystman R. 1987. Age-related changes in chest geometry during cardiopulmonary resuscitation. *J Appl Physiol* 62(6):2212-9.
12. Edge JR, Millard FJ, Reid L, et al. 1964. The radiographic appearances of the chest in persons of advanced age. *Br J Radiol* 37:769– 74
13. Engel S. 1947. The child's lung: developmental anatomy, physiology and pathology. London: Edward Arnold
14. Estenne M, Yernault JC, De Troyer A. 1985. Rib cage and diaphragm-abdomen compliance in humans: effects of age and posture. *J Appl Physiol* 59:1842–8.
15. Givens, M.L, Ayotte, K, Manifold C. 2004. Needle thoracostomy: implications of computed tomography chest wall thickness. *Academic Emergency Medicine* 11(2): 211-213
16. Grimby G, Bunn J, Mead J. 1968. Relative contribution of rib cage and abdomen to ventilation during exercise. *J Appl Physiol.* 24:159–166.
17. Howard P, Bauer A. 1949. Irregularities of breathing in the newborn period. *Am J Dis Child* 77:592-609.

18. Howatt W, De Muth G. 1965. Growth of lung function III. Configuration of the chest. *Pediatrics* 35:177- 84.
19. Jassens J, Pache J, Nicod L. 1999. Physiological changes in respiratory function associated with ageing. *Eur Respir J* 13(1):197-205.
20. Jean-Paul J. 2005. Aging of the Respiratory System: Impact on PulmonaryFunction Tests and Adaptation to Exertion. *Clin Chest Med* 26 :469 – 484
21. Jit I, Bakshi V. 1984. Incidence of sternal foramina in north India. *J Anat Soc Ind* 33:77-84
22. Kangaroo H. 1988. Chest MRI in children. *Radiol Clin North Am* 26(2):263-75.
23. Kent R, Lee S, Darvish K, Wang S, Poster C, Lange A, Brede C, Lange D, Matsuoka F. 2005. Structural and material changes in the aging thorax and their role in crash protection for older occupants. *Stapp Car Crash J* 49:231-49.
24. Krahl V. 1964. Anatomy of the mammalian lung. In: Fenn WO, Rahn H, eds. *Handbook of physiology. Section 3, vol 1.* Baltimore: Waverly Press: 213-84.
25. Loring SH, Mead J. 1982. Action of the diaphragm on the rib cage inferred from a force-balance analysis. *J Appl Physiol: Respirat. Environ Exercise Physiol.* 53:756–760.
26. Luttgens K, Deutsch H, Hamilton N. 1992. *Kinesiology, scientific basis of human motion.* 8th ed. Dubuque, IA: Brown & Benchmark.
27. Maynard V, Bignall S, Kitchen S. 2000. Effect of positioning on respiratory synchrony in non-ventilated pre-term infants. *Physiother Res Int* 5(2):96-110.
28. Mead J, Smith JC, Loring SH. 1995. Volume displacements of the chest wall and their mechanical significance. In: Roussos Ch, editor. *The thorax, part A: physiology. Section 20, 2nd ed.* New York, NY: Marcel Dekker Inc. p. 565–586.
29. Meinert E. 1901. *About the topographic age changes in atmungsaparetes* Jena: Fischer.
30. Meredith H, Knoth V. 2007. Changes in body proportions during infancy and the pre-school years. I. The thoracic index. *Child Develop* 8: 173-7.
31. Mohr M, Abrams E, Engel C, Long W, Bottlang M. 2007. Geometry of human ribs pertinent to orthopedic chest-wall reconstruction. *Journal of Biomechanics* 40 (6):1310-7
32. Muiesan G, Sorbini C, Grassi V. 1971. Respiratory function in the aged. *Bull Physiopathol Respir (Nancy)* 7(5):973-1009.
33. Muller N, Bryan A. 1979. Chest wall mechanics and respiratory muscles in infants. *Pediatr Clin North Am* 26:503-16.
34. Openshaw P, Edward S, Helms P. 1984. Changes in rib cage geometry during childhood. *Thorax* 39:624-627
35. Perez T, Becquart L, Stach B, Wallaert B, Tonnel A. 1996. Inspiratory muscle strength and endurance in steroid-dependent asthma. *Am J Respir Crit Care Med* 153(2):610-5.
36. Pierce R, Brown D, Holmes M, Cumming G, Denison D. 1979. Estimation of lung volumes from chest radiographs using shape information. *Thorax* 34:726-33.
37. Richards CC, Bachman L. 1961. Lung and chest wall compliance of apneic paralyzed infants. *J Clin Invest* 40:273-8.
38. Rusconi F, Gagliardi L, Aston H, Silverman M. 1995. Respiratory inductive plethysmography in the evaluation of lower airway obstruction during methacholine challenge in infants. *Pediatr Pulmonol* 20(6):396-402
39. Scammon R. 1927. Studies on the growth and structure of the infant thorax. *Radiology* 9:89-95.
40. Scheuer L, Black S. 2000. *Developmental juvenile osteology.* San Diego: Academic Press. ISBN: 0-12-624000-0.
41. Smith JC, Mead J. 1986. Three degree of freedom description of movement of the human chest wall. *J Appl Physiol* 60:928–934
42. Takahashi H, Frost H.M. 1966. Age and sex related changes in the amount of cortex of normal human ribs. *Acta Orthopaedica Scandinavica* 37: 122–130.
43. Takahashi H, Absumi H. 1955. Age differences in thoracic form as indicated by thoracic index. *Hum Biol* 27:65-71.
44. Taylor J, Twomey L, Furniss B. 1983. Age changes in the bone density and structure of lumber vertebral column. *J Anat* 136: 15-25.
45. Turner J, Mead J, Wohl M. 1968. Elasticity of human lungs in relation to age. *J Appl Physiol* 25:664–71
46. Vaziri A, Nayeb-Hashemi H and Akhavan-Tafti. B. 2009. Computational model of rib movement and its application in studying the effects of age-related thoracic cage calcification on respiratory system. *Computer Methods in Biomechanics and Biomedical Engineering.* Vol. 00, No. 0, 1–8.

47. Veronica f, Carolina j, Danielle et al. 2010. Breathing pattern and thoracoabdominal motion in healthy individuals: influence of age and sex. *Rev Bras Fisioter* 14(5):411-6.
48. Wehrli N, Bural G, Houseni M, Alkhalaf K, Alavi A, Torigian D. 2007. Determination of age-related changes in structure and function of skin, adipose tissue, and skeletal muscle with computed tomography, magnetic resonance imaging, and positron emission tomography. *Semin Nucl Med* 37(3): 195-205.
49. Well D, Meier J, Mahne A, Houseni M, Hernandez-Pampaloni M, Mong A, Mishra S, Zhuge Y, Souza A, Udupa J, Alavi A, Torigian D. 2007. Detection of age-related changes in thoracic structure and function by computed tomography, magnetic resonance imaging, and positron emission tomography. *Semin Nucl Med* 37(2):103-19
50. Williams L. 2000. *Gray's anatomy*, 38th edn. Churchill Livingstone, pp 510-45
51. Yoganandan N, Pintar F. 1998. Biomechanics of human thoracic ribs. *Journal of Biomechanical Engineering* 120(1): 100-4.