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CHEST WALL MOVEMENTS DURING FETAL BREATHING IN THE SHEEP

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SUMMARY

1. Movement of the chest wall and abdomen during episodes of breathing has been measured by an ultrasound technique in ten fetal lambs.

2. The fetal thoracic and abdominal walls move inwards and outwards respectively during inspiration. The position where this transition occurs is variable.

3. Movement of the lateral thoracic walls is reduced or reversed during breathing stimulated by hypercapnia while inward dorso-ventral movement increases.

4. Deep inspiratory efforts were associated with large inward then outward movements of the lateral and large inward movements of the dorso-ventral thoracic walls.

5. No relationship was found between the amplitude of the tracheal pressure deflexions and the extent of thoracic wall movements during fetal breathing.

INTRODUCTION

During breathing in the fetus the descent of the diaphragm, the relative absence of tracheal flow and the consequent drop in intrathoracic pressure during each breath alters the shape of the thorax. Tracheal pressure records reflect the combined actions of the diaphragm, intercostal and auxiliary muscles of respiration. Quantitative measurements of the rate and amplitude of these pressure changes have been used to characterize normal and abnormal patterns of fetal breathing in the sheep (Patrick, Dalton & Dawes, 1976).

Ultrasonic pulse-echo techniques have been used by several investigators to make quantitative measurements of fetal chest and abdominal wall movements in attempts to delineate similar patterns in man. The single dimensional A-scan method described by Boddy & Robinson (1971) has been used to measure the movement of a small part of the fetal thorax or abdomen. Measurements of the differential movements of echoes originating from two parts of the thorax or abdomen have been made in attempts to remove the effects of alterations in the distance between the transducer and the fetus which results from maternal breathing movements (Marsal, Gennser, Hansson, Lindström & Mauritzsson, 1976). The movements of several parts of the fetal trunk wall have been observed using two dimensional B-scanners.

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These measurements have been interpreted in a similar manner to records of breathing activity made in fetal sheep with tracheal catheters. This interpretation relies on the presence of an acceptable relationship between tracheal pressure and chest wall movements but no basis for this has been demonstrated.

The relationship between changes in tracheal pressure and the shape of the fetal thorax and abdomen has therefore been examined in chronically catheterized fetal sheep.

METHODS

Ten fetal lambs were catheterized at a sterile operation as described by Dawes, Fox, Leduc, Liggins & Richards (1972). Their ages at operation were 110 days to term (147 days). Recordings were begun 12–24 hr after operation and continued for 2 to 25 days.

Chest wall movements were measured using the transit time between pairs of ultrasound transducers. Epoxy-coated piezoelectric crystals (Mullard PXE5) 3 mm square were inserted through a skin incision and sutured to the underlying muscle on opposite sides of the fetal trunk. The skin was closed over the transducers and the flexible connecting wire was brought out along a skin tunnel to reduce stress on the wire and to prevent the transducer twisting. The area of the chest over which the transducers were implanted is shown in Fig. 1. Chest wall movements were measured in both lateral and dorso-ventral directions.

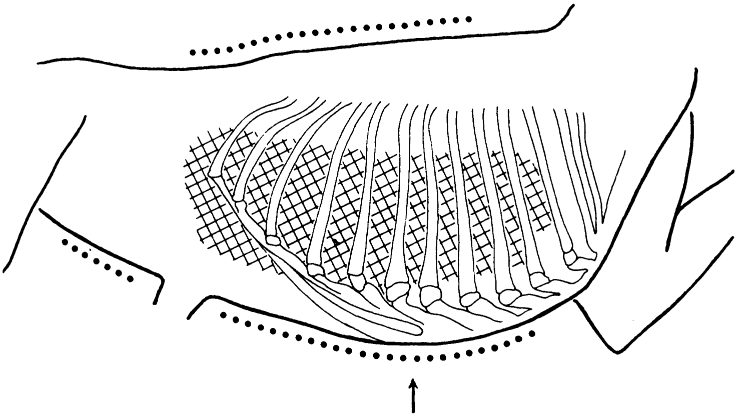

Fig. 1. Diagram of a fetal lamb trunk showing the area over which ultrasound transducers were implanted to measure chest and abdominal wall movements in dorso-ventral (along dotted lines) and lateral (hatched area) directions. Arrow shows the position of the xiphisternum.

A frequency of 2 MHz was used to excite the transducers so that they could be pulsed at rates up to 2 kHz. This ensured adequate frequency response when several pairs were scanned in sequence to measure changes in shape of the fetal trunk. The combination of the 2 MHz frequency, a wide beam width ($\pm 30^\circ$ at 20 db) and the capacitance of the transducer and connecting cable ($\sim$ 110 pF) permitted the use of crystals of convenient dimensions for implantation. A wide beam width was needed to ensure that transmission was maintained between the transmitting and receiving transducers despite slight flexing of the transducers during a breathing movement. Small crystal dimensions kept timing errors to a minimum.

A saline-filled catheter was implanted into the trachea to measure the intra-thoracic pressure. The transient response of the catheter and transducer system (Bell & Howell) was compared with that of a solid-state catheter-tipped pressure transducer (Gaeltec, Skye). The response to a -20 mmHg pressure change indicated that no significant distortion of the pressure deflexions caused by fetal breathing was present in the catheter system.

Hypercapnia was induced by administering 3 % CO_2 with 18 % O_2 in N_2 at 40 l./min to the ewe through a polythene bag placed over her head (Boddy, Dawes, Fisher, Pinter & Robinson, 1974). In four experiments in which eight fetal arterial blood samples were taken there was a rise of carotid arterial P_{CO_2} of $10{\cdot}4 \pm 0{\cdot}33$ mmHg, while the P_{O_2} remained constant and the pH fell slightly from 7·35 to 7·27.

Recording and analysis. Tracheal pressure and chest wall movements were processed on-line by a PDP 11/34 computer programmed in Assembler and Fortran. Each signal was low-pass filtered at 50 Hz (40 db/decade) and sampled at 10 msec intervals. A program was written to identify the amplitudes of the peaks and troughs of each signal, the times at which they occurred, and to calculate the maximum velocity of the chest wall movement for each inspiration and expiration. Data on up to 1025 breaths from each recording period was filed on disc. Subsequently, the breathing pattern was regenerated and displayed on an $X-Y$ plotter along with other information produced by programmed analysis. Tracheal pressure deflexions $< 0{\cdot}5$ mmHg were not examined since these lay close to the noise level of the catheter and transducer system.

RESULTS

The chest and abdominal wall movements associated with three classes of fetal breathing are described. Each represents a different level of respiratory activity. The majority of fetal breathing at the gestational ages used in these experiments is episodic, of rapid (1–5 Hz) but irregular rate and is characterized by small tracheal pressure deflexions (95 % < 5 mmHg). The largest deflexions (20–40 mmHg) were associated with comparatively long (~ 500 ms) isolated (1–4/min) breaths or 'gasps' as they have been frequently termed (e.g. Dawes *et al.* 1972). These deep inspiratory efforts occur spontaneously under normal physiological conditions in fetal sheep. Inspiratory activity with similar pressure deflexions has been described in a number of species under asphyxial conditions (e.g. Towell & Salvador, 1974) and before fetal death (Patrick *et al.* 1976). Tracheal pressure deflexions of an intermediate amplitude were obtained by making the ewe and fetus hypercapnic. The rate, regularity and amplitude of the low amplitude breathing increased under these conditions.

Low amplitude breathing. During inspiration the thoracic dimensions were reduced while the abdominal dimensions increased; during expiration they returned to their original positions. Occasionally an increase in the lateral dimensions of the thorax was recorded, usually with breaths of large amplitude. The point on the ventral surface at which inward movement of the thorax merged into outward movement of the abdomen (the 'hinging point') was examined.

Six equally spaced transducers (receivers) were placed from high on the thorax to below the umbilicus on the ventral surface of the fetus. Two transducers (transmitters), one for the upper three and one for the lower three transducers, were placed on the dorsal surface. Fig. 2 shows the movements of the upper five transducers. The three sections (*A*, *B*, and *C*) were taken from a single breathing record lasting an hour. In *A* the upper four transducers moved inwards during each breath, while the lower abdominal transducer moved in a less predictable manner, sometimes inwards, or outwards, or inwards and then outwards, or was occasionally stationary. The 'hinging point' thus lay close to this transducer. In *B* it had moved between the two abdominal transducers since the lower consistently moved outwards and the upper inwards. In *C* the 'hinging point' lay at the xiphisternal transducer since both the abdominal transducers moved outwards and both the thoracic inwards.

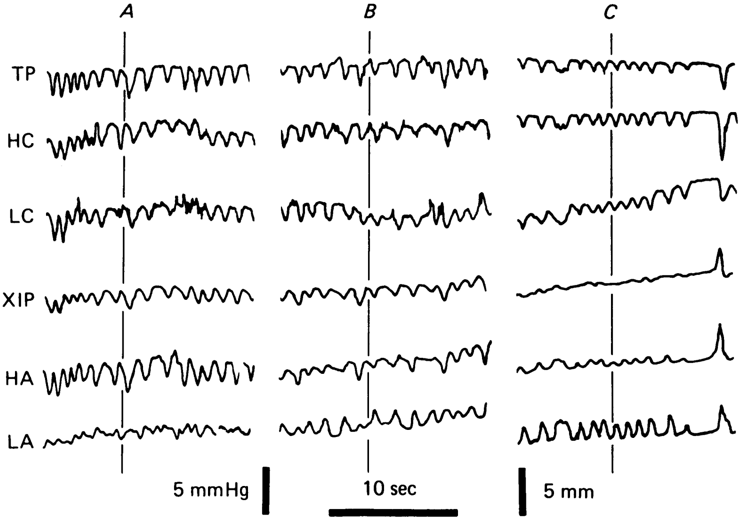

Fig. 2. Three sections of record showing simultaneous movements of five transducers placed along the ventral surface of the fetus in the mid line. They illustrate the variable position of the 'hinging' point where outward abdominal wall movement fades into inward thoracic wall movements. The fine vertical line in each panel is positioned at the beginning of inspiration, as shown by tracheal pressure, and aligns the five movement traces. TP, tracheal pressure; transducers HT, high thorax; LT, low thorax; XP, xiphisternum; HA, high abdomen; LA, low abdomen.

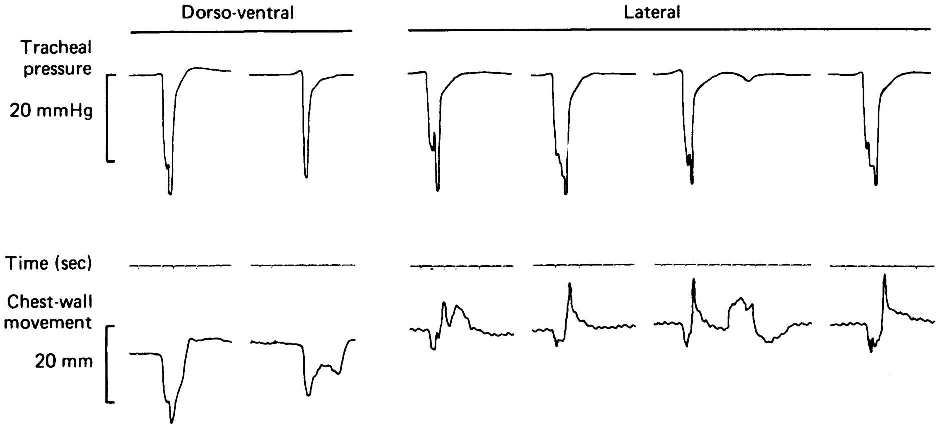

Fig. 3. Chest wall movements recorded during six sequential deep inspiratory efforts by pairs of transducers placed mutually at right angles at the level of the xiphisternum.

Deep inspiratory efforts. A detailed examination of the movements of the chest wall in both lateral and dorso-ventral aspects was made. Two pairs of transducers were implanted, mutually at right angles, at the level of the xiphisternum. Fig. 3 shows, during a bout of spontaneous deep inspiratory efforts, that the dorso-ventral dimension of the chest decreased, often by as much as 15 % of the diameter of the thorax. The lateral transducers first moved inwards, then outwards and finally to an intermediate resting position. These combined movements usually ranged over 20 %

Table 1. Direction and size of chest wall movement at the level of the xiphisternum during normocapnia and hypercapnia

Transducer placement	Conditions	Inward movement (mm; mean ± S.E.)	% breaths with inward movement	Total no. breaths
Dorso-ventral	Normocapnia	1·65 ± 0·12	81	17638
	Hypercapnia	3·79 ± 0·42	93	1298
Lateral	Normocapnia	2·65 ± 0·09	81	14677
	Hypercapnia	1·73 ± 0·75	67	3725

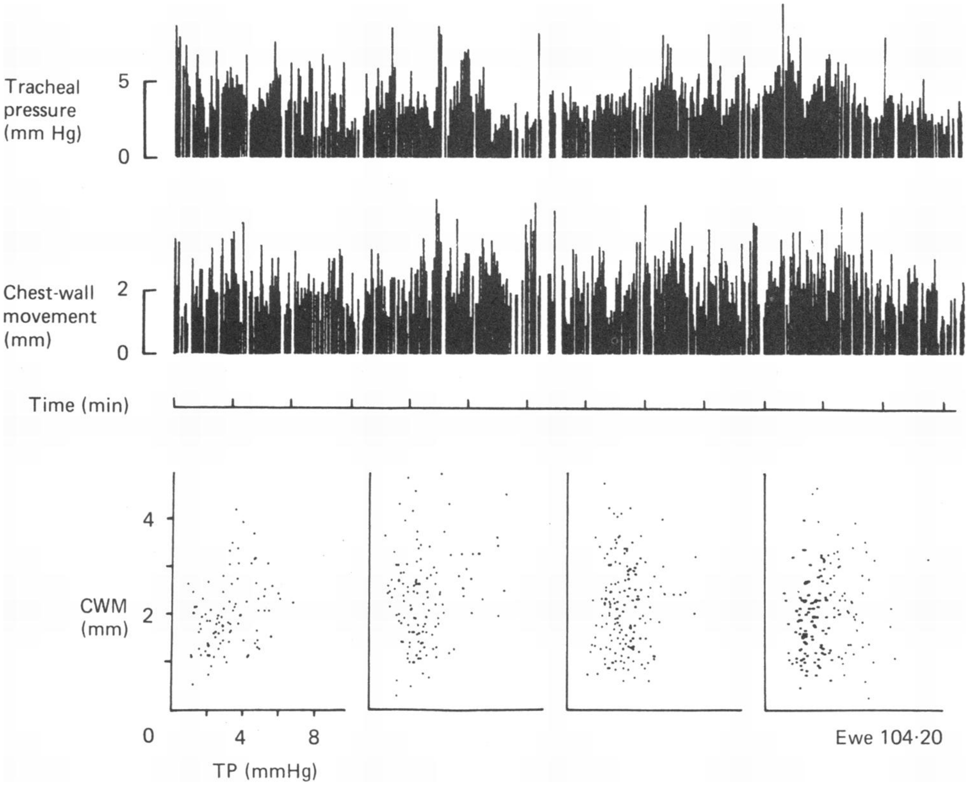

Fig. 4. Fetal breaths (1025) recorded from laterally placed transducers at the level of the xiphisternum. Each scattergram is related to the section of breathing directly above and illustrates that no simple relationship exists between the amplitudes of tracheal pressure (TP) and chest wall movement. (CWM).

of the thoracic diameter. Sometimes the chest wall stabilized at the resting diameter before moving outwards. When deep inspiratory efforts occurred during low amplitude breathing the chest wall movement which resulted was not sufficiently different to unequivocally identify this kind of breath from the normal breathing movements.

Hypercapnia. During hypercapnia the mean tracheal pressure deflexions increased from 3·26 ± 0·11 to 5·57 ± 0·51 mmHg. Movement in the dorso-ventral aspect increased while that in the lateral aspect decreased (Table 1). The proportion of breaths in which the lateral chest wall moved outwards increased, while that for the dorsoventral diameter fell.

The relationship between tracheal pressure and chest wall movements. Over 100 records were made encompassing more than 100,000 breaths. Each record contained chest wall movements measured with a single pair of transducers at the level of the xiphisternum (lateral or dorso-ventral) under constant gaseous conditions (normocapnia or hypercapnia). Each was analysed to examine the relationship between the amplitude of tracheal pressure and chest wall movement.

Very similar results were found in all the analyses irrespective of transducer location on the chest or the blood gas status of the fetus. The analysis from a pair of laterally placed transducers under normocapnic conditions will illustrate these findings (Fig. 4). The amplitude and time of occurrence of each breath was regenerated from the computer file. A 13 minute record of 1025 breaths was divided into four sections and the amplitude of tracheal pressure changes was plotted against chest wall movement. There was no significant association between them.

The possibility that there might be periods of good correlation over shorter periods of time was examined by performing a continuous regression analysis on each breathing record. The slope (M) and the constant (C) in the regression equation,

$$\text{Tracheal pressure} = M \times \text{chest wall movement} + C,$$

and the correlation coefficient (r) were calculated for a constant number of breaths along the record. The number of breaths (or time interval) on which the regression analysis is performed influences the period over which a good correlation must exist before it becomes apparent (i.e. if the regression encompasses many breaths, short periods of good correlation will be missed). Several records were analysed using 10–200 breaths in the calculation, which at average breathing rates corresponds to a time interval of 9 sec–3 min. All records were finally analysed over 40 breath intervals ($\sim$ 30 sec), a compromise between masking short periods of good correlation and erratic fluctuations in the regression coefficient. However, the actual number of breaths used in the calculation did not critically affect the results or their interpretation.

Fig. 5 shows a continuous regression analysis of the breathing record of Fig. 4. The ratio between the amplitudes of tracheal pressure and chest wall movement for each breath was also computed and plotted; this should tend to a constant value during periods of good correlation. This was never the case. Periods of 'good correlation' where $r > 0{\cdot}4$ (1 % significance level) almost exclusively reflect the entry or exit from the regression sample of single breaths at some distance from the centre of the scattergram distribution. This accounts for the similarity between the slope and the correlation coefficient, and a periodicity in these variables of similar length to the regression interval.

Movement of the abdominal wall during a breathing episode was less predictable and more erratic than that of the chest, and the point about which the thoracic and abdominal walls appeared to hinge was variable (Fig. 2). A detailed analysis of the relationship between abdominal wall movement and tracheal pressure was not performed.

Changes in the over-all shape of the chest, persisting for many minutes, occurred from time to time. The amplitude of these occasionally reached 2–3 mm, and they are probably caused by fetal and maternal movements. These gross chest wall movements were measured by plotting the diameter of the fetal chest at the start of each inspiration (line 7, Fig. 5). The correlation between tracheal pressure and chest wall movement was not altered by these changes of chest diameter, or when the transthoracic distance was any particular value.

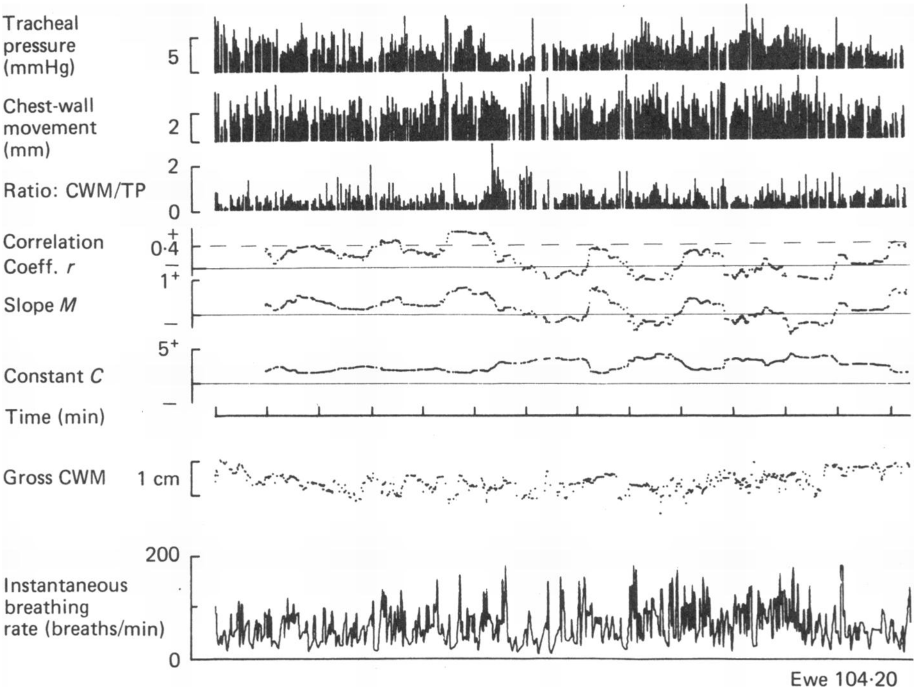

Fig. 5. A continuous regression analysis of the record in Fig. 4 performed over a 40 breath interval in an attempt to identify short periods of good correlation between the amplitudes of tracheal pressure and chest wall movement. M and C are the regression coefficient and constant in the regression equation, TP $= M \times$ chest wall movement $+ C$.

There was no association between the instantaneous breathing rate and the correlation between tracheal pressure and chest wall movement. The breathing rate increased and became more regular during hypercapnia, but no changes in correlation occurred despite a reduction in the gross changes of chest diameter, which was more pronounced in the lateral direction.

DISCUSSION

During fetal breathing activity in sheep the thoracic walls usually move inwards and the abdominal walls outwards, a pattern similar to that observed in human fetuses (Mantell, 1976; Patrick, Fethersten, Vick & Voegelin, 1978) and the newborn of both species during rapid eye movement sleep (Henderson-Smart & Read, 1978). The point on the ventral surface where the transition between inward and outward movement takes place is variable and depends on the amplitude of the breathing and probably the posture and position of the fetus. Measurements of the movement at a single point on the ventral surface will provide an inaccurate record of the incidence of fetal breathing, especially if the point lies between the upper abdomen and the lower thorax. B-scan ultrasound systems in which the movement of the entire ventral surface is visible should accurately delineate the presence or absence of breathing, although the value of accurate measurements of abdominal wall movements is uncertain.

Lateral chest wall movements, although of greater amplitude than those in the dorso-ventral direction during normal fetal breathing, tend to become smaller as the depth of breathing increases. The occasional absence of such movement renders this an inaccurate measure of breathing incidence.

The lack of a relationship between the amplitude of tracheal pressure and the movement of the chest wall, even for short lengths of time, shows that the chest wall does not behave predictably during the descent of the diaphragm. It is possible that the intercostal muscles and other accessory muscles of respiration are also active in the fetus and that they influence the mechanical response of the thorax. Electromyographic activity has been recorded from intercostal and abdominal muscles in fetal sheep, and also from the muscles which run parallel to the spine in the thoracic region (D. Walker, W. Gardner, B. Johnston & G. S. Dawes, unpublished observations). Inspiratory intercostal activity was present during some of the low amplitude, irregular breathing and the appearance and disappearance of it was often associated with activity in the abdominal and spinal muscles suggesting that the fetus had moved at this time. Phasic intercostal activity decreased between 108 and 133 days gestation, which supports the observations of R. Harding (personal communication) who found little tonic or phasic intercostal activity during low amplitude irregular breathing after 130 days gestation. The occasional deep inspiratory efforts always involved the intercostal muscles. It is possible that the occasional entry and exit of intercostal and abdominal muscle activity during normal breathing results in the variable mechanical response of the fetal chest wall.

During hypercapnia there is an increase in the amplitude of tracheal pressure deflexions and a reduction or reversal of lateral chest wall movements. This is probably the result of the stabilizing action of intercostal muscles on the thorax, because hypercapnia has been shown to increase phasic intercostal activity, and to cause it to appear at sites which were previously silent (D. Walker, W. Gardner, B. Johnston & G. S. Dawes, unpublished observations). The increase in dorso-ventral chest wall movement during hypercapnia probably occurs because this aspect of the thorax is not stabilized by the intercostal muscles.

There are a number of possible reasons for the variable nature of abdominal wall movements: curvature of the fetal spine, the position of the hind limbs, pressure of the uterine wall or activity of the abdominal muscles could all modify the reaction of the abdominal wall to the descent of the diaphragm. These experiments provide no evidence as to the factors which control the effect of fetal breathing activity on the dimensions of the fetal thorax and abdomen. They do show, however, that an interpretation of the pattern of chest wall movement based on breathing patterns measured from the trachea cannot be justified.

The degree to which these findings are applicable to fetal breathing in man is uncertain since the shape of the thorax and the precocity of the young in the two species differ. The extent, velocity and pattern of chest wall movement is similar in the two species and it seems unlikely that the intercostal muscles are always totally silent in fetal humans, especially under abnormal physiological conditions. Their tonic or phasic involvement in breathing will complicate the interpretation of recordings of chest wall movement. One noteworthy difference is that in man dorsoventral movements of the trunk are more pronounced than lateral movements. The difference probably stems from the more circular nature of the fetal trunk in man which makes recording movements of the ventral surface more attractive.

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