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THE RESPIRATORY RATE AND VENTILATION IN THE NEWBORN BABY

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Proper treatment of respiratory insufficiency in very early life must obviously depend on a knowledge of the normal respiratory pattern in the neonatal stage. Dohrn (1895), using a spirometer with face mask and valves, made the first attempt to find data for normal respiratory behaviour in newly born babies. This instrument had a dead space of more than 50 c.c., which is now believed to be more than twice the average tidal air of the sleeping infant. Murphy & Thorpe (1931) used a body plethysmograph but the figures they obtained were very variable, probably due to restlessness on the part of the baby. It would seem to be necessary to design an instrument in which the infant will sleep as comfortably as in its own cot.

The difficulty with a plethysmograph is to effect a satisfactory seal, so that the mouth and nose are open to the outside air while the body is enclosed within the airtight instrument. Previous workers made the seal round the neck of the infant, generally using rubber sheeting coated with heavy grease. Any sealing device involving the neck must be applied most gently. Unfortunately, the circumference of the neck varies with crying, which causes vascular engorgement, and the contour of the neck changes with any movement of the head. It follows that confidence can only be placed in the adequacy of the seal if rigid tests are applied with monotonous frequency. Further, if there is any degree of congestion of the veins in the neck it will not be certain that there is no damming up of the drainage from the respiratory centre. Lastly, both from published results and from personal observation, it is known that it is very difficult to ensure that a normal infant sleeps peacefully while a neck seal is in place. Observations on the resting minute volume demand complete comfort and relaxation on the part of the subject.

THE PLETHYSMOGRAPH

The instrument (Cross, 1949) was constructed after some preliminary work on a plethysmograph based on the model of Deming & Washburn (1935). A reliable and comfortable seal is so important that a new approach was attempted copying a helmet used by divers in the Japanese navy in the recent war. This helmet was fastened to the head by means of a rubber seal which passed along the rami of the mandibles to the mastoid processes and so over the occiput. Almost the entire course of such a seal is over bony structures, so that a considerable pressure can be applied without impeding free flow along veins, arteries and trachea.

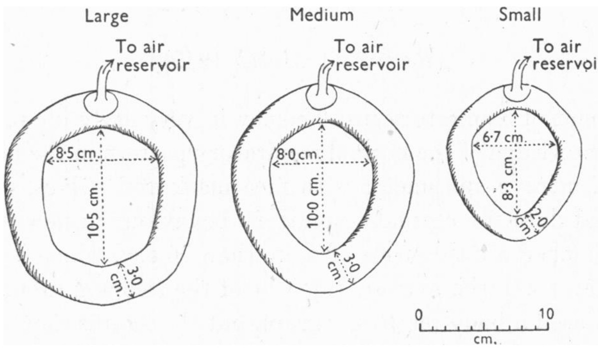

Fig. 1. Diagram to scale showing the three pneumatic cuffs.

By the kind co-operation of Mr Gorham of the Dunlop Rubber Co. a pneumatic cuff was constructed in the form of a shaped ring which was applied in such a way that it accurately framed the face of the baby when viewed from the front. The internal diameter of the ring fits across the sub-mental region of the jaw, crosses the mandible and passes along the ascending rami to the temporal region and so roughly along the coronal sutures to complete the circle near the anterior fontanelle. The outer circumference of the pneumatic cuff completes the seal by pressing against a wall built into the lid of the plethysmograph. The cuff is inflated from a reservoir, and a pressure between 45 and 60 mm. Hg is maintained within it to effect an airtight seal. Three cuffs have been consstructed, for premature, for normal and for larger infants. Fig. 1 gives details of the shapes and dimensions of these cuffs. As the cuffs are made of very soft rubber and are inflated, it is not necessary to model an individual cuff for each baby. By adjusting the slope of the cuff within the walled enclosure of the lid it is possible to use the same lid for either the medium or the large cuff, a separate lid being used for the small cuff.

The plethysmograph is rectangular in shape, and is made of 14-gauge brass. The dimensions are 59 cm. long × 30 cm. broad × 26 cm. deep. The joints are made by bolting the sheets of brass to $\frac{3}{8}$ in. angle brass, and by soldering to obtain an airtight junction. The upper edge of this brass box is finished with an out-turned flange of 1 in. angle brass. Particular care was taken to see that the up-facing flange formed a true plane. Vertical rods are soldered into the outer part of this flange to form guiding rails for the lid. This lid is made of $\frac{1}{4}$ in. Perspex, pierced by a hole near one end. This hole is 15·8 × 12·5 cm. and is lined with a wall of $\frac{1}{8}$ in. Perspex, which projects 1 cm. above the level of the lid and approximately 4 cm. below it. When the instrument is in use the junction of the lid to the brass box is made airtight by laying a continuous ring of sponge-core rubber, $\frac{1}{4}$ in. in diameter, round the flange and internal to the vertical rods. The lid is held in position with twelve paper clips of the 'Bulldog' type (Fig. 2).

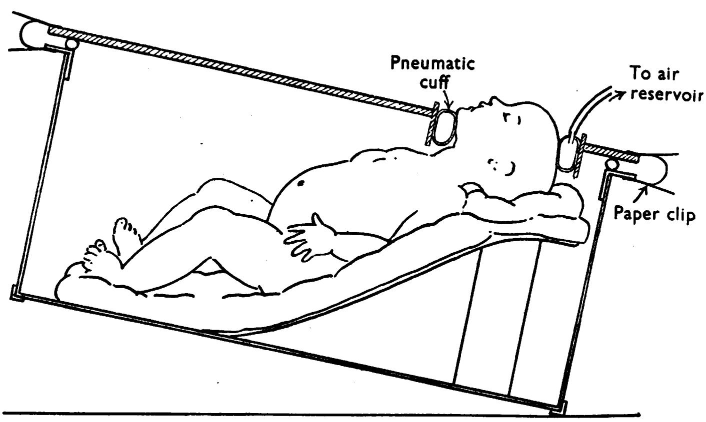

Fig. 2. Diagrammatic longitudinal section through the plethysmograph with a baby in position and the seals in place. In fact, the baby would be wearing its normal clothes and be covered with blankets.

Inside the plethysmograph there is a padded metal cradle for the baby. This cradle allows the infant to lie on its back, and supports the head so that the head lies naturally within the walled enclosure in the lid. The cradle slopes downwards from the head, to form an angle of about 25° with the floor of the plethysmograph. In order to prevent the baby from sliding down its cradle, the whole instrument is inclined at an angle of 10° towards the head. The result of these adjustments is that the infant's body slopes downwards at an angle of about 15° in the horizontal plane. This rather complex arrangement is necessary in order that the head may be slightly extended on the body, and thus keep the anterior chest wall of the infant well away from the lower lip of the walled enclosure of the lid. (It should be remembered that the newborn infant has a chest whose antero-posterior diameter is almost the same as its transverse diameter.)

The ink-writing volume recorder

If one can achieve comfort and a trustworthy airtight seal, the only problem remaining in measuring the volume of the infant's respiration is to have an accurate and sensitive volume recorder. This recorder has to be able to accommodate considerable volumes, so that a record of vigorous crying can be obtained. The seal must not be broken even by a maximal breath, and yet the recorder must produce a reasonable deflexion for such a small volume as 20 c.c. which is the average tidal air of a newborn baby.

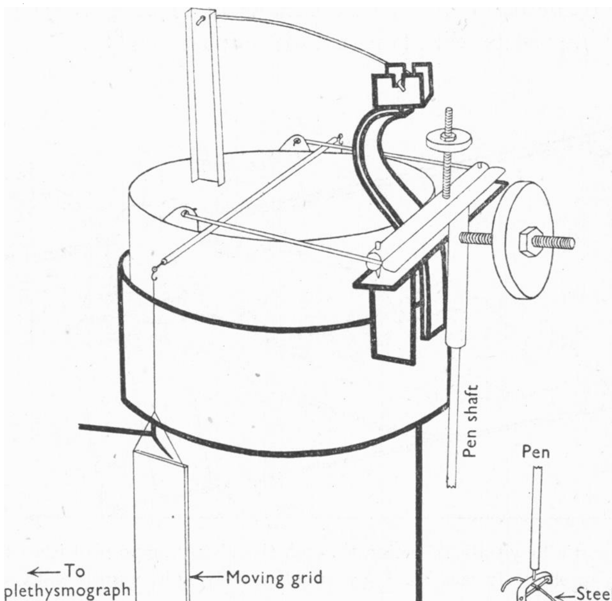

Fig. 3. Ink-writing volume recorder (semi-diagrammatic). All moving parts are drawn with thin lines, and stationary parts with thick.

The volume recorder is built into the upper part of one of the side walls of the plethysmograph, near the foot end, and the float chamber is adjusted to be horizontal when the instrument is at its normal 10° slope. In order to avoid the build-up of pressure and undue current formations, a short brass tube of 7·5 cm. diameter was used to join the volume recorder with the plethysmograph. The recorder itself is of the Krogh type. A kinematic suspension maintains the float horizontal, but permits vertical movement through a small arc of a large circle. The float is constructed of brass foil, six-thousandths of an inch in thickness, and all the attachments are made of the lightest possible material. In place of knife edges, which are difficult to adjust, the volume recorder pivots on two hardened steel points (gramophone needles). These points are correctly positioned when placed in two minute pits indented into a steel plate. The float is counter-balanced by two weights at right angles, which are adjustable on threaded brass (Fig. 3). It is possible to adjust the recorder so that it will maintain any position in which it is placed. As the sealing fluid, liquid paraffin, is somewhat viscous, and sticks to the wall of the float chamber, it was decided to adjust the counter-weights so that the volume recorder is slightly bottom heavy and comes to rest in the mid position. As it seemed desirable to have an instrument which would record faithfully the respiratory volume changes of an infant which might at times be breathing or crying at the rate of 80 or more respirations per minute, it was decided to sacrifice some of the initial high sensitivity by two methods of damping.

Damping was produced by the use of liquid paraffin, specific gravity about 0·8, as sealing fluid, and by making the float run up and down in an annular channel 0·7 cm. wide. Dynamic calibration showed that these two methods were effective in giving a faithful record of rapid changes in volume. In the early part of this work a frontal writing lever was used, with a smoked drum, but as the subjects for the study were newborn infants who may not be removed from their nursery, it was found to be much more convenient to use an ink-writing device. This was achieved by having a vertical lever which sweeps to and fro across a continuously passing stream of 'Manifoldia' paper. The pen consists of a No. 24 s.w.g. tube, which syphons the ink from a container set astride the paper.

Calibration of volume recorder

Two methods of calibration were used; static and dynamic. For the purpose of static calibration the plethysmograph was closed with a plain Perspex lid, and sealed in the usual way with paper clips. A test for leaks was performed by placing a weight of 9·5 g. (one penny) on the top of the float of the volume recorder. On removal of the penny the pen should return to its zero position. This test is the one routinely employed when the instrument is in use. When even a small leak was present, there was a rapid drift with the penny test. When the system was leak-proof, successive volumes of 20 c.c. of air were introduced into the plethysmograph through a brass tube soldered into the head end of the box. After a complete sweep of the paper, 20 c.c. volumes were successively withdrawn, and measuring and averaging of the results showed that there was no consistent variation between one side of the paper and the other, and the heights described did not vary among themselves by more than the error introduced by measuring them (0·5 mm.). By this static method of calibration it was found that a vertical deflection of 1 cm. represented a volume of 28·8 c.c.

Dynamic calibration

Though a baby's respiration is not represented by a simple harmonic wave, it was thought that the reliability of the volume recorder could be tested with a sine wave over a large range of speeds and volumes; an accurate response at a rate much higher than a normal infant's breathing, would justify confidence

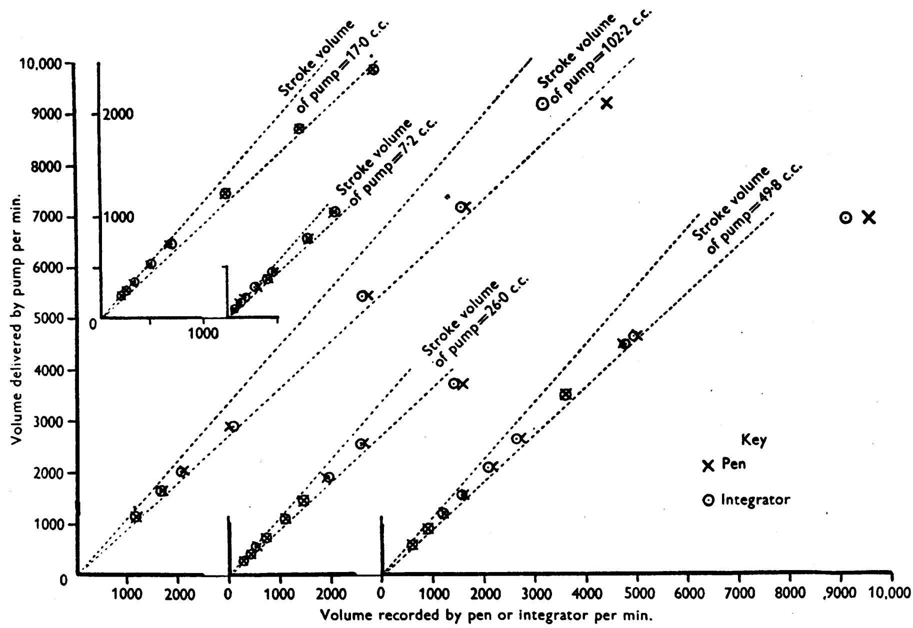

Fig. 4. Dynamic calibration of the volume recorder at five different stroke volumes of the pump. The scale for ordinate and abscissa is the same, but in order to keep the curves separate, the ordinate has been shifted for different curves. The dotted lines represent the 10% error lines for each curve, that to the left representing understatement by the pen or integrator, that to the right representing overstatement. For any given reading the number of cyc./min. of the pump may be calculated by

$$\frac{\text{volume delivered by pump/min.}}{\text{stroke volume of pump}}.$$

In the inset graph (top left) the scales have been doubled.

in results obtained from infants breathing at the lower rates. For this purpose a tube of 1·7 cm. diameter was soldered into the plethysmograph and was connected by a stiff rubber tube to an animal respiration pump from which all valves had been removed, so that a given volume of air was simply added to and removed from the plethysmograph by each stroke of the pump. The pump was set to deliver five volumes, between 7·2 and 102·2 c.c. per stroke (as measured by water displacement from a burette), and the speed was regulated to give ten rates between 11·3 cyc. and 144 cyc./min. The results of the dynamic calibrations for different volumes are given in the composite graph,

Fig. 4. It will be seen that there is an accuracy of $\pm 10\%$ for the automatic integrator (see below) for any of the specified throws of the pump with rates up to 100/min.; but with the higher rates and larger volumes there is a considerable over-statement by the volume recorder. This is more pronounced by the pen than by the automatic integrator, the probable explanation being that the pen records not only the over-swing of the float, but also some 'whip' of its own.

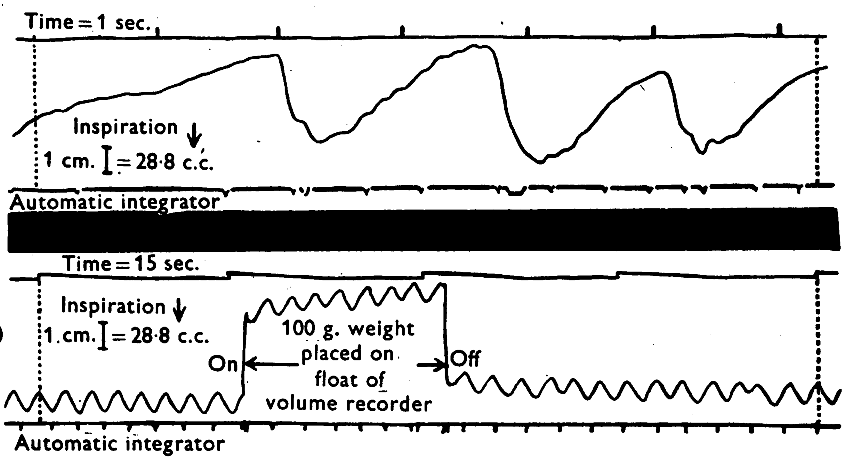

Fig. 5. (*a*) Tracing from baby crying vigorously. Note rapid inspiration. The volume recorder cannot record this rate of volume change faithfully. (*b*) Tracing from sleeping baby. The 100 g. weight on the float raised the pressure in the plethysmograph by 11 mm. of water. Note that there is no gross change in the volume or rhythm of the respiratory tracing. A leak is disclosed with this pressure.

This undoubtedly introduces a serious error with the crying infant where 100 c.c. or more may be inspired in 0·4 sec. (see Fig. 5*a*). Also, while crying the infant will move its head and open its mouth which will make the pneumatic cuff bulge farther into the plethysmograph and displace air. No attempt has been made to estimate the error involved in recording crying volumes. The results given here are from the sleeping infant only.

Error in reading results

In order to estimate the minute volume of the infant in c.c., one has to measure the vertical height in cm. of all the inspiratory movements recorded in 1 min., and multiply this height by the static calibration factor of 28·8. The thickness of the line described by the pen is less than 0·5 mm., and one aims to measure the heights to the nearest half mm.

Automatic integrator

The chief error in estimating the volume that the infant has breathed in a minute probably arises from fatigue on the part of the observer, for, in order to work out the results from an hour's trace, the height of many hundreds of lines must be measured. This operation is not only potentially inaccurate, but also very time-consuming, and, as it was hoped to undertake a considerable survey of newborn infants, Roberts & Widdas (1949) constructed an 'automatic integrator for volume recorders'. Fig. 4 shows a series of graphs of the overall dynamic calibration of the volume recorder, where the volume fed into the plethysmograph per minute is plotted against the volume described by the pen (from linear measurement) and by the automatic integrator. It is found that a deflexion of 1 cm. by the pen represents a volume change of 28·8 c.c. One count on the Post Office counter is equivalent to a volume change of 41·7 c.c.

As the pen describes a line which moves irregularly about a mean position on the paper, it is justifiable in using the automatic integrator to halve the volume recorded in order to measure the air inspired in 1 min. This is based on the assumption that the pen starts and ends each minute at its mean position. The errors involved from this assumption are greatly diminished if the volume of inspired air is averaged over a period of 5 min. or more.

By using this automatic integrator it is possible to obtain records from several babies in one day, and the results are immediately available. This compares very favourably with the 5 or 6 hr. work which had to be done on each tracing before the integrator was available.

'Back pressure' in the apparatus

Using the damping methods described above, it is apparent that the instrument may allow the build-up of a certain amount of back pressure. However, a water manometer attached to the plethysmograph gave a swing of less than 1 mm. with a sleeping infant. This may possibly be important since this apparently minute pressure may affect the infant's respiration and also may affect the accuracy in recording. To test the first possibility, it was decided to increase the pressure within the plethysmograph greatly and to observe the infant for any signs of alteration in respiration. Weights of 50 and 100 g. were placed either on the float of the volume recorder or were suspended from the counter-weight. These weights gave pressures up to ± 11 mm. water. Examinations of the records taken under these conditions showed no change in respiratory rate and no gross change in volume (Fig. 5*b*). The actual volumes were not measured, as the volume recorder could not be trusted when so greatly out of balance. The second possibility seems to be ruled out by the overall dynamic calibration of the instrument.

TECHNIQUE

Selection of subjects. The subjects for this study were taken from normal babies delivered in the Maternity Wards of St Mary's Hospital.

No conscious method of selection was used. If the baby was judged to be normal by the clinician in charge, and the mother willing, the selection was generally made by the Sister in charge of the ward. At one point in the series it was found that many more females than males had been examined, and for a period the Sister was therefore asked to select a male child when possible. There was a certain prejudice in favour of getting repeated examinations on one child, in order to test the results of previous observers. It should be noted that in order to obtain the comparatively few results here published, over 100 infants have been placed in the plethysmograph, but only those who have fulfilled the criteria of rest defined below are quoted.

When the infant was first introduced into the plethysmograph, and after an airtight seal was obtained, it was found that there was a certain amount of baseline drift on the volume recorder, due to expansion of the air within the instrument as it was warmed by the infant's body. The small pipe which was soldered into the plethysmograph for the static calibration was connected to a three-way tap and well-oiled 50 c.c. syringe by means of rubber tubing, so that the volume of air in the plethysmograph could be conveniently adjusted without having to disturb the airtight seal.

When a record was to be taken, if the weather were cold, a warm rubber hot water bottle was placed in the instrument for a few minutes. The cradle was padded with two or three blankets and the infant was taken from its cot and placed in the plethysmograph. It was covered with the same number of blankets as were used in its cot, and the exact height of the padding beneath it was adjusted until it was thought that the head was suitably placed to fit centrally within the walled enclosure of the lid. The lid was now placed in position, and a finger passed between the lower lip of the wall and the infant's chest, to ensure that there was no contact here. If the position were satisfactory, a suitable cuff was placed round the head, and inflated from the air reservoir. After inflation, slight minor adjustments were made to remove creases or wrinkles. The paper clips were now applied to the lid, and the record commenced. A test for leaks was made with a penny, as described, and if this was satisfactory no further adjustments were needed.

Although the manipulations as described here may seem complicated, it was not at all unusual for an infant to be taken from its cot and placed in the plethysmograph, with an airtight seal, without waking the infant. More often, some crying occurred, but if the baby did not quickly settle down it was given a bottle of warm water to suck, and in nearly all cases this induced sleep. On a number of occasions the rectal temperature was taken before and after the hour's test. Except in the rare case of the fractious child, who cried vigorously throughout the examination, the rectal temperature was not increased.

To determine the minute volume of inspired air for the sleeping infant, it was necessary to define carefully a reasonable test period on a subject which is notoriously active. Figures given by other workers have been based on differing standards. Thus Deming & Hanner (1936) take 'representative half-minute periods', while Murphy & Thorpe (1931) select three half-minute periods from their traces, where the infant exhibited the slowest respiratory rates, and measured the volume inspired in this period. Only results obtained under the following conditions are presented:

(1) To minimize the metabolic stimulus of food, readings were taken only between 1½ and 3½ hours after meals. (The normal infants in this nursery are on a 4-hourly feeding regime.)

(2) The infant must have been quiescent for at least 20 min. before the part of the record used here commenced.

(3) The resting minute volume was obtained from a period of *not less than* 5 (up to 18) consecutive minutes, during which time the infant was sleeping quietly without any limb activity, facial grimaces or sucking movements. The minute volume is expressed as an average of such a period, provided that there were satisfactory tests showing no leak from the plethysomograph before and after the test period.

In practice the majority of the records lasted for about an hour, and in those where the infant rapidly settled down it was possible to show, by plotting minute volume against time, that the infant achieved a fairly steady resting level. The test was confined to this period of 1 hr. because of the potential danger from the pressure of the cuff round the face, which is near the systolic blood pressure of the normal infant, 80 mm. Hg (Woodbury, Robinow & Hamilton, 1938). In fact, no ischaemic changes occurred in the faces of the infants examined, beyond the expected temporary reactive hyperaemia.

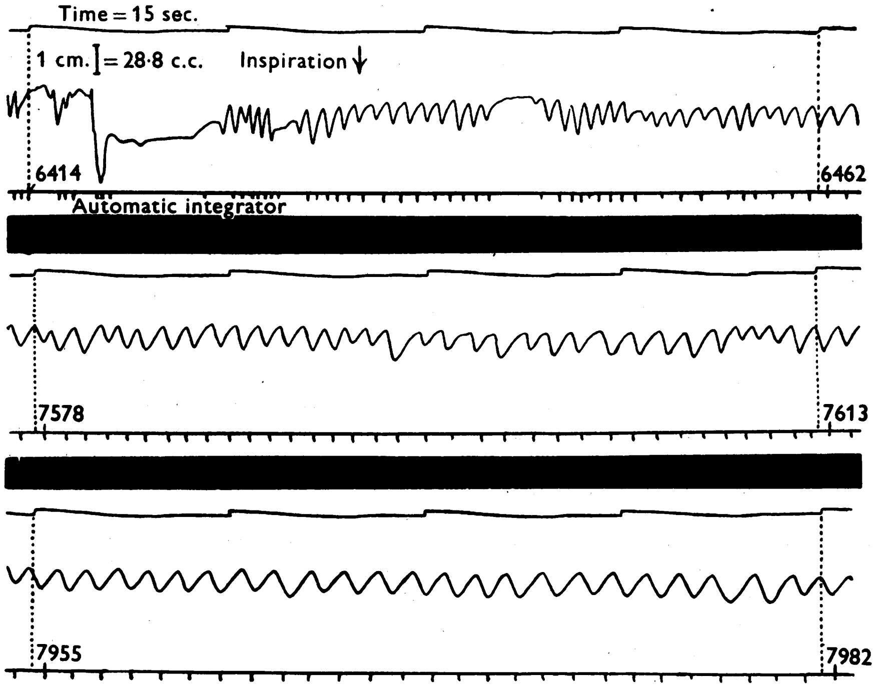

Fig. 6*a*.

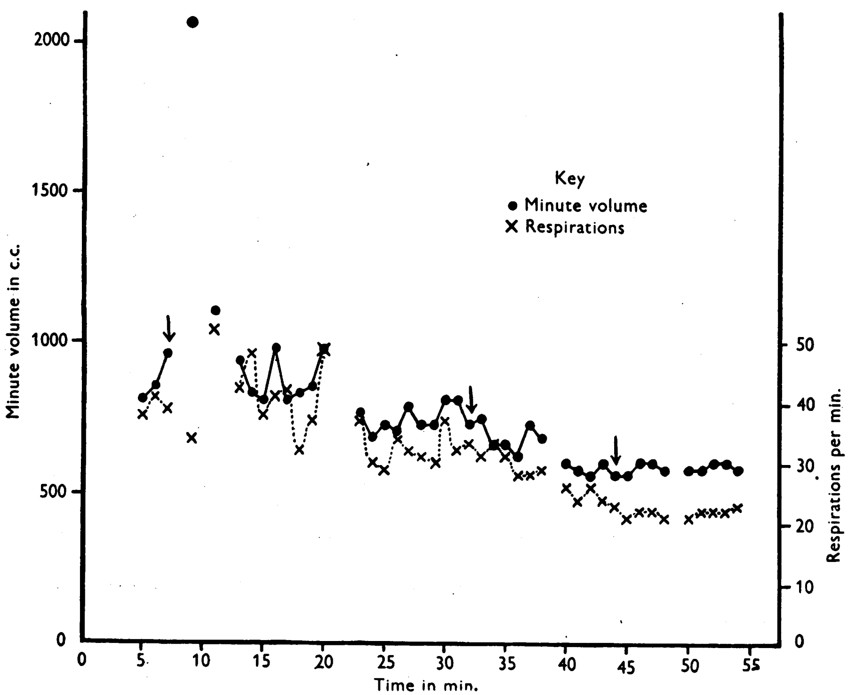

Fig. 6*b*.

For explanation of Fig. 6 see p. 469.

RESULTS

Three separate minutes of a trace from baby M1 are shown in Fig. 6, and with it the graph made for the whole period of the trace. This infant was chosen because the minute volume on this occasion approximates most closely to the mean minute volume for the whole series of babies examined.

TABLE 1

Date (1948)	Name	Sex	Age (days)	Weight lb.	Weight oz.	Period averaged (min.)	Minute volume Range (c.c.)	Minute volume Average (c.c.)	Respiratory frequency Range (per min.)	Respiratory frequency Average
17/3	D	M	4	7	2	5	511– 601	556	18–27	22·9
17/3	R	F	0·5	7	14	5	444– 598	542	23–30	26·0
22/3	H	F	1	8	6	5	504– 633	585	19–30	27·2
5/4	B	M	1	5	9	6	654– 739	690	28–38	32·4
22/10	M	F	0·5	8	7	7	591– 696	651	29–34	31·0
22/10	W	M	2	8	5	6	605– 688	661	34–39	36·5
26/10	W	M	6	8	10	7	646– 813	754	18–33	26·6
29/10	W	M	9	8	13	6	605– 729	677	20–29	25·3
22/10	W1	M	4	7	4	5	542– 625	600	30–35	32·5
25/10	B1	F	1	6	15	10	647– 730	683	34–41	36·8
25/10	G	M	3	6	12	12	605– 750	690	33–51	37·9
27/10	R1	F	13	7	3	8	584– 647	618	30–37	32·6
1/11	G1	M	3	10	15	12	917–1022	973	29–37	32·3
5/11	G1	M	7	11	0	12	708– 855	795	20–34	28·9
2/11	M1	F	3	7	2	11	438– 522	493	26–40	32·7
5/11	M1	F	6	7	0	9	479– 563	535	25–36	28·8
12/11	M1	F	13	7	7	9	563– 604	586	21–26	24·7
5/11	W2	F	10	8	4	12	667– 771	722	28–35	30·1
10/11	R2	F	5	7	5	6	583– 646	615	24–29	27·2
10/11	J	F	5	8	2	7	562– 646	622	19–22	20·8
10/11	M2	F	0·5	8	4	13	479– 646	557	25–33	28·3
13/11	M2	F	3	8	0	11	500– 646	567	33–44	37·8
17/11	M2	F	7	8	4	14	480– 563	526	25–32	28·4
19/11	C	F	0·2	6	14	12	313– 375	349	14–21	19·0
22/11	P	F	3	6	8	14	438– 585	513	28–36	33·2
26/11	P	F	7	6	12	14	543– 668	598	32–40	36·0
29/11	P	F	10	6	13	12	585– 688	624	29–36	33·3
29/11	J1	F	4	6	2	18	396– 647	493	18–35	24·7
30/11	W3	F	0·3	7	12	6	501– 585	539	20–25	22·7
1/12	W4	M	1	7	5	10	480– 668	543	23–25	24·0
3/12	H1	M	3	7	10	7	605– 668	638	38–41	39·6
8/12	L	M	4	8	2	7	354– 396	369	20–29	24·7
10/12	L	M	6	8	1	9	438– 485	466	22–33	29·1
13/12	S	M	9	6	13	9	480– 543	515	24–27	25·3
13/12	L1	M	4	6	12	6	417– 563	487	26–31	28·1
18/12	B2	M	7	7	4	7	354– 459	384	22–24	22·4

Table 1 gives the results from the infants who showed a satisfactory resting period as defined above. These are given in chronological order, save that repeated observations on one infant, made on different days, are brought

Fig. 6 (*a*) Baby M1, 12 November 48. Three separate minutes from the respiratory trace. (*b*) Graph of the whole trace from the same baby, with arrows marking the minute periods which are figured above. Where the graph is discontinuous, the tracing was not satisfactory for analysis because adjustments were being made, a leak was present or a test for leaks was being made. Between the 40th and 48th minutes the criteria mentioned in the text were satisfied, and so the average for this period has been accepted as the resting value.

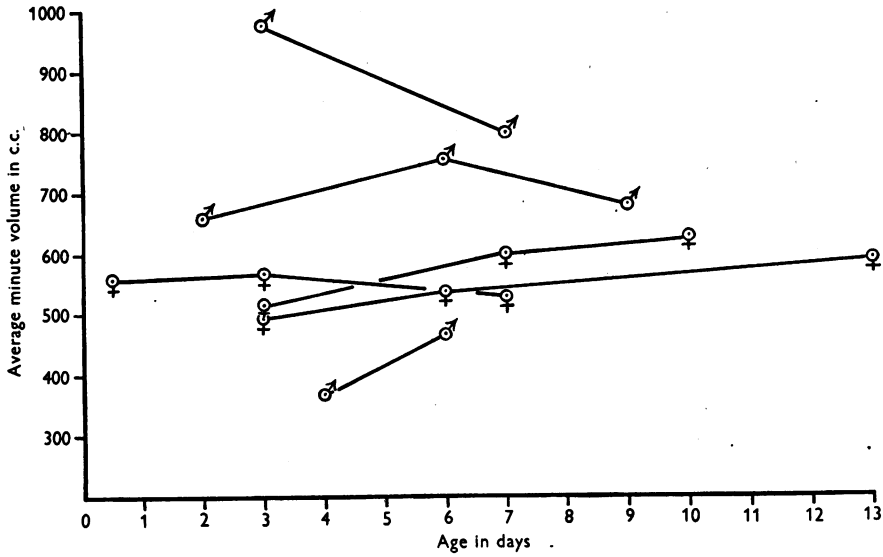

Fig. 7. Average minute volume in those babies who have been examined on more than one occasion. The straight lines link the repeated observations on one baby and are not meant to indicate any speculation on the volume a baby was breathing between observations.

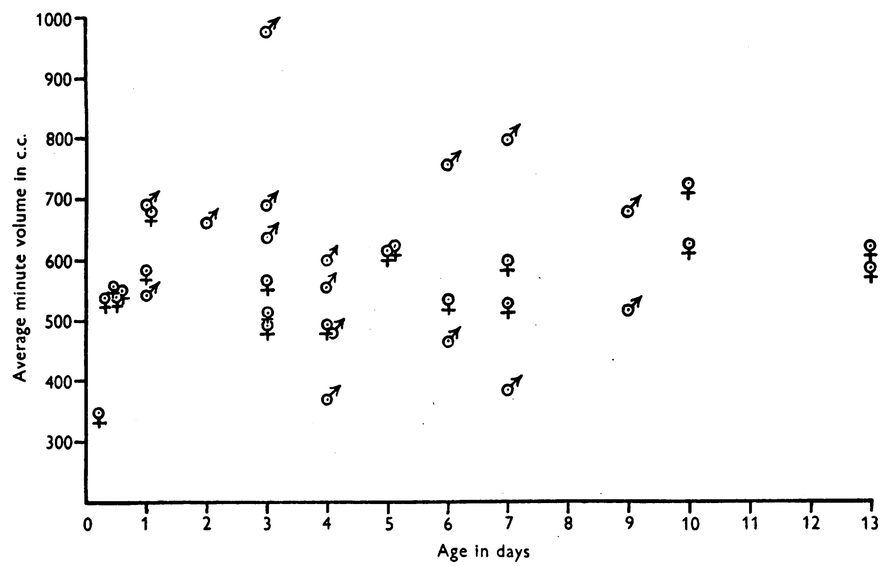

Fig. 8. Average minute volume in c.c. related to the age of the infant.

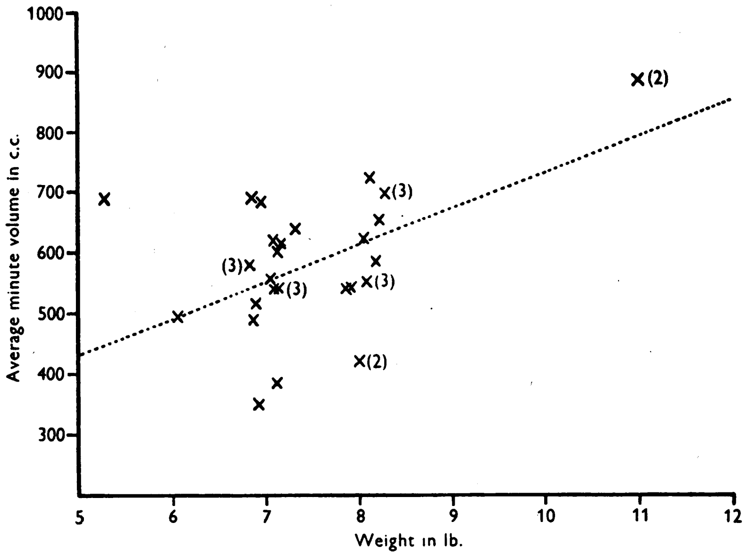

Fig. 9. Average minute volume in c.c. related to weight of subject. The numbers in brackets after six of the points indicate the number of separate records from this infant which have been averaged to give the weight and minute volume charted (see text). The dotted line is the calculated regression line based on these figures.

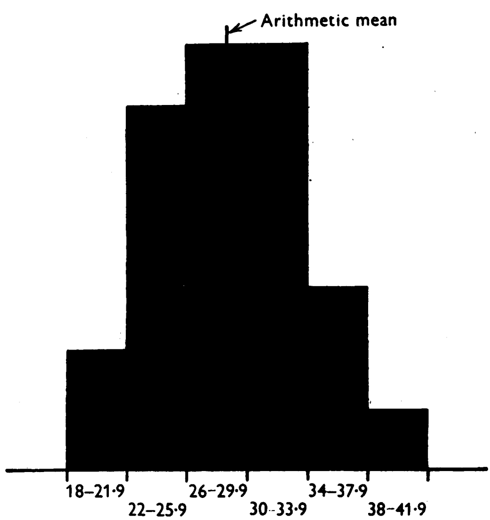

Fig. 10. Frequency distribution polygon showing average respiration frequency/min. in the sleeping infant. Where there are repeated observations on one infant the mean of the values has been taken.

together to facilitate comparison. It will be seen that in a particular baby during the first 13 days of life there is no consistent trend towards an increase of average minute volume with increase of age, which is contrary to the general belief, and to the statement of Murphy & Thorpe (1931) on rather inconclusive evidence from four babies. This point is illustrated in Fig. 7.

The average minute volume in c.c., plotted against the age and weight of the infants respectively, is shown in Figs. 8 and 9. In Fig. 9 the calculated regression line (see statistical note) is drawn. It was realized that it might well be of more significance to consider the minute volume of air breathed in relation to the surface area of the infant, but the only available information on surface area of infants was from the work of Lissauer (1903), in which he states that surface area is equal to $10{\cdot}3 \times \sqrt[3]{\text{weight}^2}$. This assumes that all babies are of identical shape and, in fact, for the weight range concerned, gives what is virtually a straight line relationship between weight and surface area. For this reason the weights of the infants, which are measurable, have been used rather than the hypothetical surface areas.

The frequency distribution polygon for the average respiratory rates of the infants studied is shown in Fig. 10. It will be seen that the shape suggests that a fair sample of infants has been examined. The average respiration rate is 28·64/min., with a standard deviation of $\pm 5{\cdot}195$.

STATISTICAL ANALYSIS

By P. Armitage

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There are altogether thirty-six observations on twenty-six babies. Three observations are available for each of four babies, and two observations for each of two babies.

The data were examined in relation to two questions:

(*a*) Is there any evidence that, for an individual baby, the changes in A.M.V. (average minute volume) in the first 15 days or so of life are related to changes in weight or age?

(*b*) Disregarding the variation between successive readings on the same baby, is there any evidence that the variation between A.M.V. readings for different babies is related to the differences between the weights and ages of the babies?

The first question is answered by calculating the partial regression coefficients of A.M.V. on weight and age for those babies on whom more than one observation is made, each of the three variables being first reduced by subtracting the mean value for the baby concerned. It was found that neither of the partial regression coefficients of A.M.V. on weight or age (for fixed values of age or weight, respectively) were significant; nor were the ordinary regression coefficients of A.M.V. on weight or age. There is therefore no evidence in the present data that changes in A.M.V. for individual babies are related to changes in weights or age.

The second question is answered by calculating the partial regression coefficients of A.M.V. on weight and age, using the actual values for the different babies, and taking averages when there is more than one reading for any of the babies. The partial regression coefficient of A.M.V. on age for fixed weight is non-significant, but that of A.M.V. on weight for fixed age is significant. We may therefore ignore the effect of age and calculate the ordinary regression coefficient of A.M.V. (in c.c.) on weight (in oz.). This is found to be 3·6740 with a standard error of 1·1170. The value of Student's t is 3·289 (on 24 degrees of freedom), which would be exceeded by chance less than once in 100 times.

The mean A.M.V. is 589·33 c.c. with a S.E. of 19·35, and the mean weight is 122·528 oz., with a S.E. of 3·464. The equation of the estimated regression line is

$$\begin{aligned} y &= 589{\cdot}33 + 3{\cdot}6740\ (w - 122{\cdot}528) \\ &= 139{\cdot}17 + 3{\cdot}674w, \end{aligned}$$

y being the A.M.V. in c.c. and the w the weight in oz. The standard deviation of the scatter about the regression line is estimated as 116·1 c.c.

DISCUSSION

With this plethysmograph, in which it is possible to get the subject sleeping with some ease, it is to be expected that the average values obtained for respiration rate and minute volume will be lower than those of previous workers. In fact this is the case.

Thus Deming & Hanner (1936), in a study of eighteen normal infants in the first 11 days of life, find an average respiration rate of 44/min., with a range of 23–82/min. In the present series the average is 28·64/min., with a range between 14 and 51/min. Despite the satisfactory state of rest obtained, there are still quite striking variations when repeated 'satisfactory' examinations are made on one baby. Thus baby W shows rates of 36·5, 26·6 and 25·3 on different days. No explanation is offered for this, beyond the possibility that the criteria for rest are not sufficiently stringent.

Similarly, when dealing with average minute volumes, Deming & Hanner find an average which varies for different days of life between 734 and 1144 c.c./min. and a range between 225 and 1774 c.c. In this study the average is found to be 589 c.c./min., with a range between 313 and 1022 c.c./min. In view of the fact that these writers take their results from only ½ min. periods and it is possible for a baby to hold its breath for such a time, it is surprising that the limit of their range is not lower. One can only conclude that their subjects were far from experiencing normal rest.

Deming & Hanner found that there was a relationship between the average minute volume and the weight of the infant, and state that the volume of air breathed increases by something between 38·1 and 248·1 c.c./lb. body wt. The average value was 127·3 c.c., which is rather more than twice the value obtained in this study. Shaw & Hopkins (1931), in their study of premature infants, find a figure of 193 c.c./lb. body wt., which is equivalent to 10 c.c./oz. body wt. compared with the present figure of 3·674 c.c./oz.

SUMMARY

1. A new form of body plethysmograph for measuring the respiratory volume and rate of the newborn infant is described.

2. The seal is effected with a pneumatic cuff round the bony points of the face and head, thus leaving the trachea, veins and arteries free from obstruction.

3. With this instrument it is believed that one can approach normal resting conditions.

4. The mean average respiration rate of the infant in the first 13 days of life is 28·6 (S.D. = 5·2) resp./min.

5. The average minute volume of the infant in the first 13 days of life is found to be 589 c.c./min.

6. Evidence is given to show that there is positive relationship between the weight of the infant and the volume breathed per minute.

7. No such relationship is found for age.

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REFERENCES

Cross, K. W. (1949). *J. Physiol.* **108**, 37 *P.*

Deming, J. & Washburn, A. H. (1935). *Amer. J. Dis. Child.* **49**, 108.

Deming, J. & Hanner, J. P. (1936). *Amer. J. Dis. Child.* **51**, 823.

Dohrn, R. (1895). *Z. Geburtsh Gynäk.* **32**, 25.

Lissauer, W. (1903). *Jb. Kinderheilk.* **58**, 403.

Murphy, D. P. & Thorpe, E. S. (1931). *J. Clin. Invest.* **10**, 545.

Roberts, P. W. & Widdas, W. F. (1949). *J. Physiol.* **108**, 37 *P.*

Shaw, L. A. K. & Hopkins, F. R. (1931). *Amer. J. Dis. Child.* **42**, 335.

Woodbury, R. A., Robinow, M. & Hamilton, W. F. (1938). *Amer. J. Physiol.* **122**, 472.