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Comparative Review of Techniques for Recording Respiratory Events at Rest and during Deglutition

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Abstract. The coordination between swallowing and respiration is essential for safe feeding, and noninvasive feeding-respiratory instrumentation has been used in feeding and dysphagia assessment. Sometimes there are differences of interpretation of the data produced by the various respiratory monitoring techniques, some of which may be inappropriate for observing the rapid respiratory events associated with deglutition. Following a review of each of the main techniques employed for recording resting, pre-feeding, feeding, and post-feeding respiration on different subject groups (infants, children, and adults), a critical comparison of the methods is illustrated by simultaneous recordings from various respiratory transducers. As a result, a minimal combination of instruments is recommended which can provide the necessary respiratory information for routine feeding assessments in a clinical environment.

Key words: Instrumentation — Respiration — Transducers — EDAT — Deglutition — Deglutition disorders.

There is growing interest in the relationship between respiration and swallowing as the normal pattern of events requires a high degree of coordination in all age groups. The speed of events is too fast to see with the naked eye, thus the use of instrumentation is helpful in the study of deglutition. The unobtrusive monitoring of respiration during feeding is important in the study of dysphagia and hence the accuracy, sensitivity, and response time of the techniques for doing so are crucial in providing precise information for the feeding therapist. Many methods of recording respiratory patterns have been reported, each having its own characteristics and not necessarily measuring the same respiratory parameters, which sometimes leads to conflicting, or at least superficially different, data being reported in the literature.

In order to compare information between groups in a valid way it is important to first fully understand the behavior of the instrumentation itself before attempting to understand the information received from patient monitoring. Often the instrumentation applied is not well characterized. The purpose of this paper is to rectify this by examining and evaluating most of the methods commonly used for the study of respiration and swallowing, thus permitting exploration of a basis of transducer selection for each particular aspect that interests the feeding therapist. These different transducers have proved simple to apply and are capable of giving results which, while providing the required information, are little prone to artefact. The authors' experience is based on a continuing study program of feeding investigations involving over 100 normal children, a similar number of adults, over 100 premature and mature infants, as well as large numbers of stroke patients and 180 other neurologically impaired subjects, most with cerebral palsy.

Description of Techniques for Recording Respiratory Information

As illustrated in Figure 1, there are two main techniques for monitoring respiration: direct airflow (oral, nasal, or both oral and nasal airflow being monitored) and some type of measurement related to changes in inflation of the lung, often called respiratory effort (focuses on movements of chest and abdomen, accessories to respiration).

The respiratory events associated with a swallow start with airflow falling rapidly to zero, where it remains

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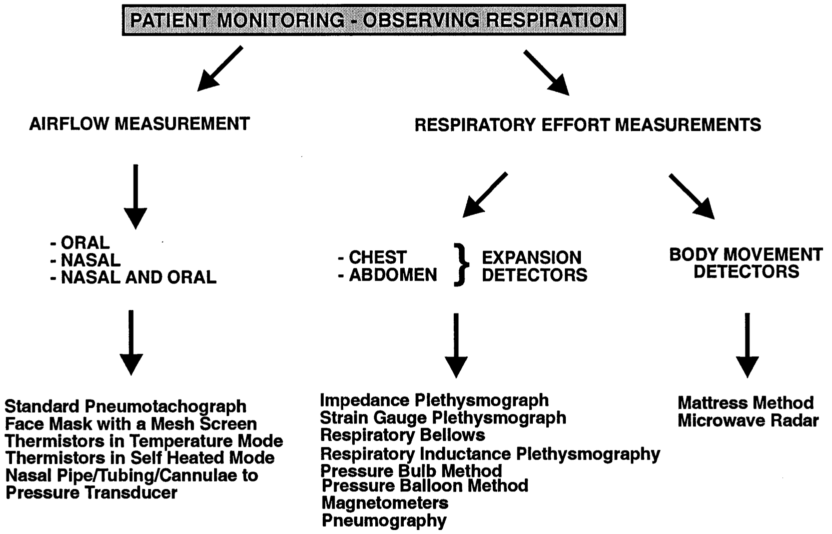


Fig. 1. A summary of methods for monitoring respiration.

for an average duration of 0.6 sec, and ends with a rapid onset of airflow. This period of zero flow between functionally significant airflows is referred to by some workers as a ''respiratory pause'' [1] or an ''apneic pause'' [2]. Apnea, which may be central, obstructive, or mixed, is often defined [3,4] as a cessation of airflow lasting 5 sec or more (depending on the author). However, the cessation of flow associated with swallowing is sufficiently characteristic to merit the term ''swallow apnea,'' which is used in this paper.

In considering which technique to use for swallowing studies, the particular needs of the subject group must be examined and a combination of criteria will limit the number of appropriate transducers. There are three groups of subjects: adults (e.g., normals, stroke patients), children (e.g., normals, those with neurological conditions), and infants (e.g., premature, term neonates, older babies) where the technology has to be applied. Tables 1, 2 and 3 give examples of respiratory monitors used to study these groups in current research—for resting (R) and/or feeding (F) studies. It is essential, particularly in premature infants who are classified as being at risk, that any respiratory measurement should not compromise the subject. It is also crucial that the transducer(s) chosen are acceptable to the subject without imposing stress, e.g., a successful test on a child with cerebral palsy involves using both the correct transducer and gaining the child's and the Caregiver's confidences.

Direct Measurement of Airflow

When measuring direct airflow, consideration as to whether to record oral and nasal airflow must be made. There is strong evidence to suggest that in normal subjects oral flow is usually accompanied by some measurable nasal flow [5,6], but it will be absent if there is palato-pharyngeal closure or the nasal passages are completely obstructed. Oral flow is difficult to measure during feeding, therefore most workers have employed nasal airflow as their preferred measurement.

There are five main groups of airflow techniques that have been used for resting and/or feeding studies, as illustrated in Tables 1, 2 and 3: thermistors (in heated or nonheated mode); nose masks; nonmask nasal pneumotachographs; CO_2 analyzers (although used for specialized purposes they are not used for routine clinical feeding studies and therefore will not be discussed); and nasal pressure measurement using a cannula of some form.

Heated Thermistor Anemometry

Heated thermistor anemometry can provide respiratory airflow measurement [7] and is a clinical tool used by Speech and Language therapists to evaluate nasality during speech [8]. A bead thermistor mounted in a protective tube carries sufficient electric current to raise its temperature to 180°C (the self-heated mode). As air flows passes over the thermistor, heat is removed more rapidly than in still air. A circuit senses the cooling effect and supplies more power to return the bead to its original operating temperature. The extra power required is a measure of the flow velocity. The bead needs to have a small heat capacity and be able to make good contact with the flowing air. Thus, a nude thermistor is preferable to a glass-coated version which many groups employ. The response time for a nude thermistor is approximately 40 ms, the output signal being almost linear against flow for flow rats $<21 \text{ min}^{-1}$ [8] (the actual response varies with the temperature of the flowing air

Table 1. Respiratory monitors used to study normal subjects

Researcher(s)	Transducer	Measurement	Feeding (F)/ Resting (R)
[30]	Strain gauge pneumograph	Chest movement	R
[31]	Cannulae inside nostril	Nasal airflow	R
[32]	Nose mask with heated pneumotachograph	Nasal airflow	F
[2]	Respiratory inductance Plethysmograph Nasal thermistor	Respiratory movement Nasal airflow	F
[33]	Nasal cannulae (EDAT)	Nasal airflow	F

Table 2. Respiratory monitors used to study children with cerebral palsy

Researcher(s)	Transducer	Measurement	Feeding (F)/ Resting (R)
[34]	Modified spirometer	Oral airflow	R
[35]	Respiratory inductance Plethysmography	Abdominal and chest movement	R
[36]	Respiratory inductance Plethysmography	Abdominal and chest movement ($\Rightarrow$ tidal volume)	F
[37]	No details of method	Nasal and oral airflow Thoracic and abdominal movement	R
[38]	Respiratory inductance Plethysmography	Abdominal and chest movement ($\Rightarrow$ tidal volume)	F and R
[39]	Magnetometer Pneumotachography with face mask	Respiratory movement Airflow	R
[40]	Nasal cannulae (EDAT)	Nasal Airflow	F
[41]	Respiratory inductance Plethysmography	Abdominal and chest movement ($\Rightarrow$ tidal volume)	R

Table 3. Respiratory monitors used to study infants

Researcher(s)	Transducer	Measurement	Feeding (F)/ Resting (R)
[42]	Mercury-in-rubber chest strain gauge Nasal thermistor bead assembly	Chest movement Nasal airflow	F
[28, 43]	Graseby pressure bulb	Abdominal movement	F
[44]	Mercury strain gauge	Abdominal and thoracic movement	R
[23]	Strain gauges Thermistor	Abdominal and thoracic wall movement Nasal airflow	F
[45]	Pneumograph expansion belt	Abdominal movement	R
[11]	Miniaturized nasal pneumotach	Nasal airflow	F
[46]	CO_2 analyzer	Nasal airflow	F
[47]	Impedance pneumography	Chest movement	F
[48]	Self-retaining nasal flowmeter Respiratory inductance Plethysmography	Nasal airflow Chest and abdominal movement	F
[49]	Total body plethysmograph Esophageal balloon	Thoracic gas volume, tidal flow Esophageal pressure	R
[50]	Small glass bead thermistor in front of nostril	Nasal airflow	R
[24]	Rubber bag on abdomen	Respiratory effort	F
[51]	Self-retaining nasal thermistor Respiratory inductance Plethysmography	Nasal airflow Abdominal movement	R
[52]	Pneumotachograph	Nasal airflow	R/F
[7]	Sensitive infant nasal anemometer thermistor	Nasal airflow	F
[1]	Nasal flowmeter CO_2 analyzer Infant respiratory bellows	Nasal airflow Oral airflow Abdominal inspiratory effort	F

Table 4. Examples of published neonatal flowmeters used for research purposes

Researchers	Flowmeter details	Method of attachment	Linearity	Resistance	Dead space
[14]	400 mesh screen on modified CPAP nasal cannula	Prongs in nares and catheter taped to forehead	to 80 ml sec^{-1}	0.13 mmH_2O ml^{-1} sec	0.35 ml
[11]	400 mesh miniaturized nasal pneumotach	Self-retaining ring inside naris	to 20 ml sec^{-1}	0.6 mmH_2O ml^{-1} sec	0.15 ml
[15]	100 mesh miniaturized nasal pneumotach	Self-retaining ring inside naris	to 20 ml sec^{-1}	0.1 mmH_2O ml^{-1} sec	0.1 ml
[53]	Nasal mask pneumotach	Clay at nostril to prevent leaks	to 5 L min	0.05 mmH_2O ml^{-1} sec each side	<1.5 cc
[52]	Adapted Fleisch pneumotach	Bulky adaptor requiring tape across head	to 12 L min		Negligible
[1]	400 mesh screen flowmeter	Self-retaining		13 mmH_2O ml^{-1} sec	0.35 ml

and between individual thermistors). The tube may be held directly in the flow stream or mounted in a mask and held over the nose and/or the mouth for resting respiratory studies. The bead is insensitive to flow direction, but in respiration studies, distinction between inspiration and expiration during regular respiration is possible as the flowing air is at different temperatures. However, when irregular or individual events occur it is not possible to identify the flow direction with a single thermistor though dual thermistor systems so permit.

Thermistors in Temperature Measuring Mode

A popular airflow technique is that employing either nude or glass-coated, positive or negative temperature coefficient bead thermistors in temperature measuring mode. For a positive temperature coefficient bead, as expired air passes over the thermistor, it warms up and its resistance rises. As air is inspired, the thermistor then cools towards room temperature with an appropriate decrease in resistance. Measurement of the changes in resistance can be used to monitor airflow. The thermistor may be placed in series with a voltage supple and a fixed resistor of an appropriate, large value to run at constant current with negligible self-heating. This arrangement has the advantage of showing flow direction but the response time (between 1 and 10 sec), though allowing continuous respiration to be recorded well, is too slow to record timings successfully and the detail of individual rapid events. A common arrangement is to mount three thermistors on a flexible stalk to record a combined flow pattern from the mouth and the nose.

Mask Pneumotachographs

The standard pneumotachograph was originally designed by Fleisch [9], and a review of suitable instrumentation is available [10]. The subject wears a mask covering nose and mouth and breathes through a mesh or set of fine capillary tubes arranged in parallel. A pressure difference, proportional to the rate of flow, appears across the mesh which offers small resistance to the flow. The mesh screen pneumotachograph has the advantages of being disposable, having a smaller dead space than the capillary tubes, and increased frequency response. Sufficient sealing between mask and face is a problem for quantification of flow, especially in infants. However, standard mask instruments or specially designed versions cannot be used for feeding tests, though the technique is the basis for many modified or miniaturized pneumotachographs, including the version used by the present authors to study infants [11–13].

Non-Mask Nasal Pneumotachographs

There are several examples of nasal pneumotachographs described in the literature (Table 4), all based upon the design of the standard pneumotachograph, employing either capillary tubes in parallel or a mesh, e.g., the flowmeter used by Wilson et al. [1] combines the flows from each naris through a single mesh. Miniaturization allows them to be kept clear of the mouth and thus they can be used for feeding studies; to date these have been used mainly with neonates when the nasal flow passes through a mesh and the resulting pressure drop is recorded. Dead space effects may be reduced by passing fresh gas continuously into the pneumotachograph close to the nares and by making sure that all redundant space is filled while maintaining low resistance [3].

The Exeter miniaturized pneumotachograph for infants (a scaled version for adults being available for the rare occasion when quantitative information is required) is based on that of Brouillette and Thach [14] and consists of a short tube which is inserted into the naris, a 100 mesh stainless steel gauze (3.4 mm diameter), and a side arm which allows measurement of the pressure difference across the mesh. The most recent design has a dead space of 0.11 ml, a resistance of 0.1 mmH_2Oml^{-1} sec, and a response time of 2m sec. A single pneumotachograph may be used to record respiratory events, as recent data suggest that both nostrils remain patent during quiet breathing even if the nasal resistance in each nasal passage varies over time [15]. For quantitative measurements, two pneumotachographs may be used to record flow information from each nostril without compromising the subject, e.g., in demonstrating the changeover of the dominant nostril in infants and adults.

Intranasal Pressure Measurement

Methods employing some type of cannula inserted just into the nose (e.g., length of pipe, silicone tubing, nasal cannulae, catheters) rely upon the reduction of pressure within the nares of inspiration and conversely, a slight increase in pressure above atmospheric on expiration due to the flowing air. By connecting the cannula to a pressure transducer the pressure changes can be detected and this proves to be a sensitive and reliable measure of the events of nasal airflow associated with respiration. Some authors have used individual catheters for each naris but the present authors find it convenient to use standard nasal cannulae (Model number 1108 Hudson Oxygen Therapy Sales Co. Temecula, CA). Although normally used to give oxygen to the patient, they are available in adult and infant sizes and can be adjusted to suit the individual by reducing the height of the nostril prongs. This system has an adequate responded time constant of 0.5m sec. Since the cannulae do not make a complete seal, quantitative measurements are not possible but the sensitivity is such that small flows can be easily registered, e.g., the cardiac artefact during an apnea with an open airway [15].

Indirect Measurement of Respiratory Effort

Respiratory effort is usually measured using either of two techniques. The first involves detecting changes in external body conformation, i.e., body movements which indicate the respiratory effort or chest wall movement detectors. For example, a pressure-sensitive pad in the cot mattress can be utilized to indicate body movements associated with respiration in babies with suspected prolonged apnea (a cessation in breathing). Chest wall movement detectors are more common; a number of groups studying swallowing use one of these techniques in isolation without examining airflow, and many more combine airflow and movement detection. The second group of methods involves observation of changes in the internal geometry of the conducting tissues in the chest, e.g., electrical impedance pneumography.

Plethysmography is the term used to describe the direct or indirect measurement of the volume or change in volume of a body part. Measurements of this type are made either from the whole body (whereby the subject is seated inside a sealed box) or from the torso. Measurements from the torso infer volume changes in the thoracic cavity from geometrical changes of the torso perimeter at different locations. During periods of quiet breathing, the chest wall moves in two orientations—since the ribcage moves in the horizontal plane and the diaphragm moves in the vertical plane. There are many similar devices which can be exploited to give the necessary readings for the geometrical changes; the main examples work on either electrical, mechanical, or pneumatic principles.

The researchers listed in Tables 1, 2, and 3 employ one of nine methods to infer respiratory effort: pneumography, strain gauge plethysmography, magnetometers, respiratory inductance plethysmography, total body plethysmography (again not conventionally used for swallowing studies), rubber bag on abdomen, infant respiratory bellows, Graseby pressure bulb, and impedance plethysmography. The first eight methods measure changes in the external conformation whereas the last measures the internal changes in impedance of the trunk.

Pneumography

Pneumography involves placing around the chest a piece of large bore convoluted tubing with trapped air inside which, connected to a pressure transducer, allows pressure fluctuations within the tubing to be recorded as the chest inflates and deflates.

Strain Gauge Plethysmography and Magnetometry

Strain gauge plethysmography employs strain gauges around the torso held in position under an elastic band and is an example of a mechanical device. Similarly, pairs of magnetometer coils can be placed at opposite ends of diameters of the trunk to infer respiratory effort from changes in mutual inductance.

Respiratory Inductance Plethysmography (RIP)

Respiratory inductance plethysmography (commercial name Respitrace, Ambulatory Monitoring Inc., Ardsley, NY) is used by a growing number of groups for measuring respiration during feeding. A design for an RIP has been given by Cohen et al. [16]. The subject has to wear zig zag loops of wire (10 cm or so in depth, therefore quite restrictive) sewn onto an elasticized body band, available in infant, child, and adult sizes. Two such bands are worn for most studies whereby movements from the abdomen and chest are separately recorded; a combined signal gives a measure of ‘‘tidal volume.’’ The measurements assume that all movement is directed towards useful respiratory flow and is related to the change in lung volume. The wire loop is part of the inductive section of a resonant circuit determining the frequency of an oscillator. As the subject breathes, there is a change in the cross-sectional area of the wire loop and this leads to an inductance change that can be measured.

The adult RIP system constructed for this study consisted of a wire (28-gauge insulated copper of resistance 3.4Ω) sewn by machine onto a length of stretch lycra material (90 cm × 10 cm). The spacing was such that 2.1 zig zags of wire were sewn per centimeter of material. The necessary voltage offset adjustment to allow for different chest sizes was provided by a potentiometer and this was reset for each individual. The frequency response of the system was measured to be flat to the limits of the experiment at 13 Hz.

Pressure Bulb Method

A simple and inexpensive method of recording respiratory effort is to employs one or more pressure bulbs (of the type normally used in conjunction with a Graseby apnea alarm for babies) (Graseby Medical Respiration Sensor, Watford, UK). The pressure bulb consists of a disk of open-cell sponge encapsulated in a soft plastic case connected by a length of flexible plastic tubing (internal diameter 1 mm) to a sensitive pressure transducer in order to extract a waveform signal. During quiet breathing, as the subject breathes in, the bulb pressure rises giving an increased voltage output from the transducer and similarly, as the patient exhales, a decrease in transducer output voltage is produced. The pressure bulb is widely used to monitor infants where there is a risk of apnea and is secured onto the abdomen with tape. This transducer may easily be used to monitor respiratory movements of other subject groups. Older ambulant children and adults breathe by making more use of the chest and accessory muscles than babies. Elasticized belts at low tension (depth of 2.5 cm) may be comfortably worn around the three locations (chest, abdomen, and across the accessory muscle region) with the bulbs held underneath.

A number of experiments were performed in the laboratory and on normal subjects to establish the frequency response of the pressure bulb. Both the effects of the open cell sponge and the length of the silicone tubing connecting the bulb itself to the pressure transducer were investigated. By imposing a sinusoidal pressure change of variable frequency generated by a loud speaker, the frequency response characteristics of a pressure bulb were shown to be flat out to 4 Hz (time constant 0.04 sec) and comparison with a simple silicone balloon catheter, which had a response of 0–40 Hz, showed that the bulb's frequency response was affected by the elastic properties of the sponge whereas shortening the connecting tube only led to an insignificant improvement. The pressure bulb's response to a controlled step pressure reduction was recorded. It was observed that the bulb settled in two distinct stages to a certain pressure as the sponge reached equilibrium following a step change. The initial response had the time constant of 0.04 sec but at later times a much longer time constant of 3.8 sec accounted for the final approach to equilibrium. The bulb response thus consists of two parts: (1) small changes are represented accurately up to 4 Hz, and (2) for a step change type of event there is a 0.04 sec initial response as before but also a longer time constant of 3.8 sec which gives rise to an artefact.

Impedance Plethysmography

The human body is a conductor of electricity and thus if its shape or conductivity change there is an accompanying impedance change. In impedance plethysmography either 2, 3, or 4 electrodes (often ECG electrodes) are placed around the chest. During respiration, the electrode spacing changes slightly due to chest wall movement and tissue movement and the action of the air filling the lungs alters the current path. The resulting measured impedance change is almost entirely due to a change in resistance caused by volume change in the lungs. The size of the impedance change depends upon the type and position of the electrodes and also on the somatotype of the subject. The existing impedance of the thorax is of the order of thousands of ohms and the change in impedance is in the tens of ohms range when measured using a constant alternating current. By utilizing a high frequency (100 kHz), low amplitude current (a few μA), the technique avoids stimulation of any sensory receptors. The impedance change and change in volume of air in the lungs during respiration are approximately linearly related and therefore it should be possible to calibrate the output voltage to a respired volume. This technique provides an accurate indication of the event and rate of ventilation; however, it is less accurate as an indicator of volume measurement. Reported artefacts include movement and cardiac interference (especially when brachycardia occurs) [17]. More important for feeding studies is that detection of obstructive apnea is apparently difficult [17]. For such studies, this method is cumbersome to apply and in dysphagic subjects it is often useful to detect and distinguish any apnea associated with the feeding problem.

For this study, the impedance plethysmograph used a four electrode system [18] and was run at 41 kHz, having a flat frequency response from 0 to 56 Hz. A pair of electrodes was placed on each side of the chest below

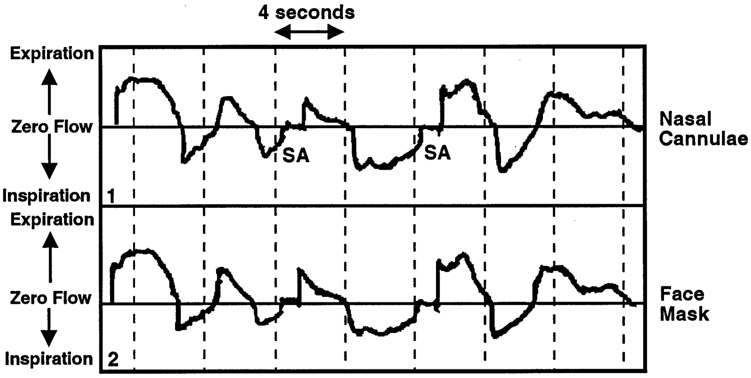


Fig. 2. Comparison of the events of nasal respiration recorded via nasal cannulae [top channel (1)] and total respiratory flow recorded by a face mask fitted with a 100 mesh screen [lower channel (2)], with the mouth closed. There are two spontaneous swallow events (SA) during the period of quiet respiration.

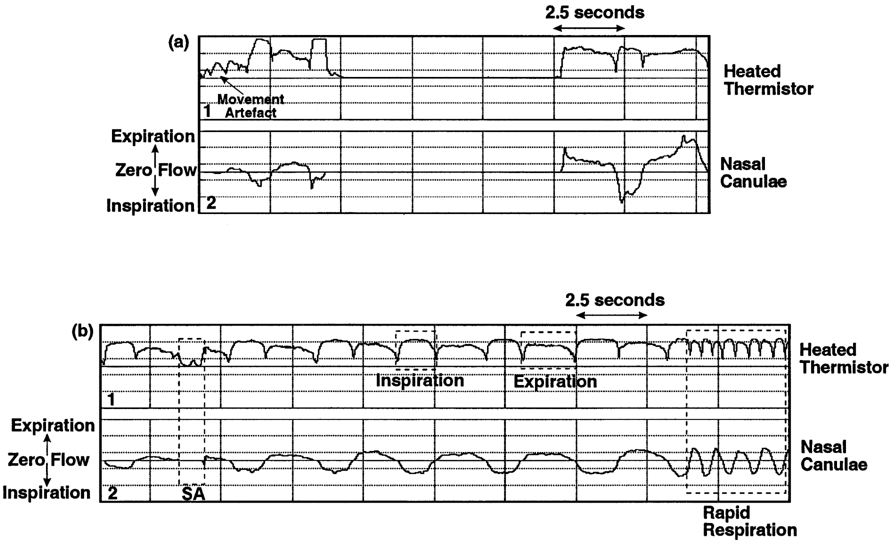


Fig. 3. Comparison of heated thermistor [upper channels (1)] and nasal cannulae [lower channels (2)] for the study of respiratory events. **(a)** Movement artefact on the thermistor trace and an apnea when true zero flow is indicated for both traces. **(b)** A swallow event (SA) occurs at the extreme left and a period of rapid respiration at the extreme right, with the dotted boxes showing the time relationships. In between there is a period of quiet breathing.

the axillae. The impedance changes were detected by a phase-sensitive detector followed by an averaging filter.

Results

The nasal airflow associated with a swallow event when a normal subject takes 5 ml of liquid from a spoon has previously been characterized by simultaneous video-fluoroscopy, nasal airflow recording, and cervical auscu-latation [19]. Because the appearance of the nasal airflow trace usually allows ready recognition of a swallow event by the brief (about 0.6 sec) cessation of airflow, the present authors favor recording nasal respiration by using nasal cannulae connected to a sensitive pressure transducer. The results presented in this section are for normal subject groups and each of the major methods for recording respiratory information will be compared with those from nasal cannulae. The direct methods of recording nasal respiration will be examined first followed by the indirect measurements of respiratory effort. During deglutition there is always a short interval when no respiratory airflow occurs. For convenience we call this interval a ''swallow apnea,'' (SA) called by some workers with infants ''suckle feeding apnea,'' since it is truly a period of zero flow, although it is much shorter than the periods normally referred to as apneas in other respiration studies.

Figure 2 illustrates the comparison between nasal cannulae and a mask held securely over the nose for recording nasal respiration leaving the mouth uncovered. The mask had a 100 mesh screen (diameter 1.5 cm) across its outlet and was large enough to fit over an adult's nose without any leaks. The two traces show similar features during both quiet respiration and during two spontaneous swallows. The study provides clear evidence that pressures recorded using nasal cannulae represent true nasal airflow events, as shown by the mask, without the inconvenience of using a mask.

Figure 3 is an example of a chart obtained when a normal subject wears nasal cannulae and a nasal an-

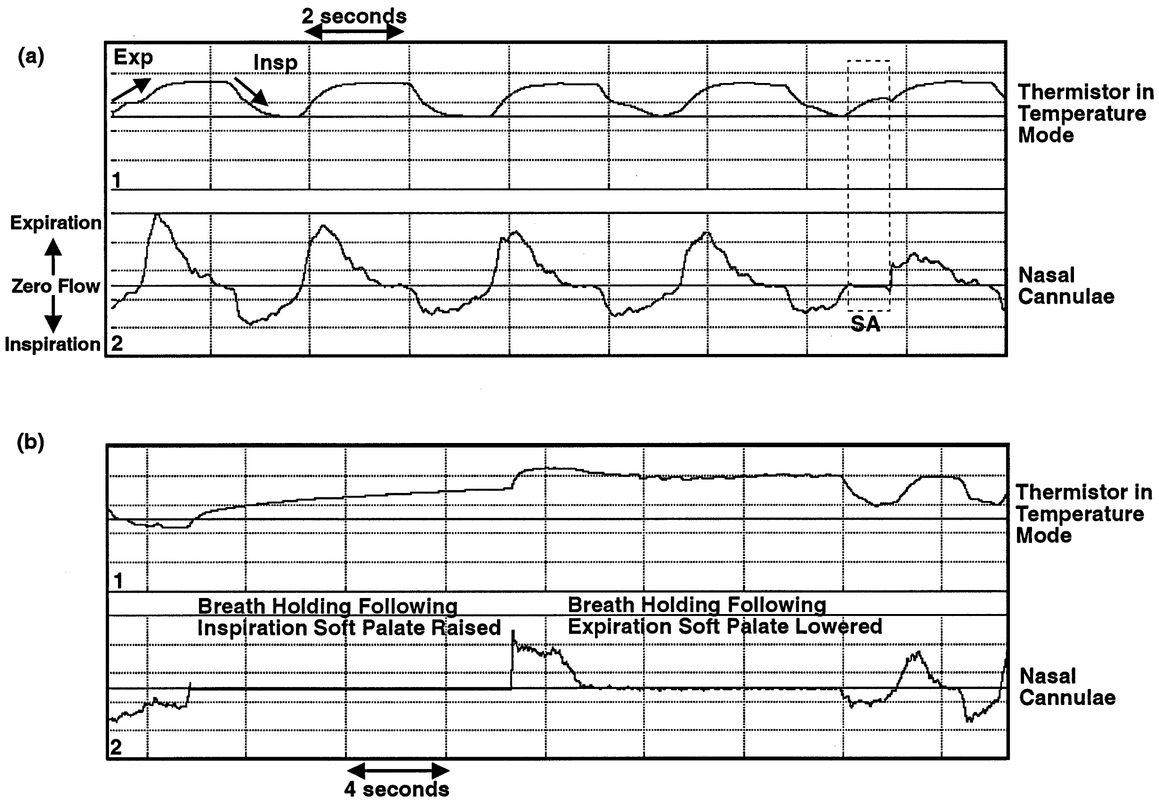
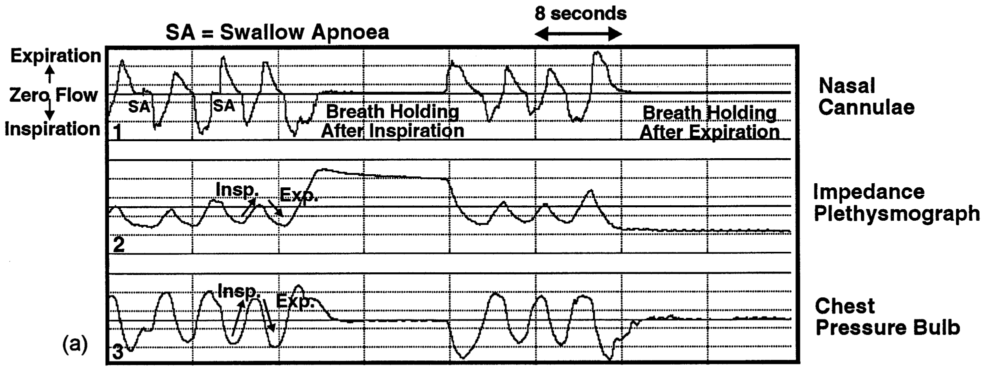


Fig. 4. Comparison of a nude thermistor in temperature mode [upper channels (1)] and nasal cannulae [lower channels (2)] for recording nasal respiration. **(a)** A period of quiet breathing with a spontaneous swallow (SA) towards the end. The upward slope in channel 1 represents expiration (Exp) and the downward slope, inspiration (Insp). **(b)** The effect of breath holding, first following inspiration with a raised soft palate and then following expiration with a lowered soft palate.

emometer mask [8] employing a heated bead thermistor during a period of quiet breathing when he voluntarily held his breath. An upward deflection from zero flow on the nasal cannulae trace depicts an expiration and any reading below the zero flow line occurs during an inspiration. Figure 3a shows where the true zero flow occurs for both the nasal anemometer (channel 1) and the nasal cannulae (channel 2) illustrating that neither instrument has a drifting zero that might lead to misinterpretation. At the beginning of 3a on the thermistor trace there is an artefact probably due to small ambient air movement not associated with nasal flow. This sensitivity to the very small flows due to movement is significant when attempting to monitor respiration in abnormal subjects, particularly in children with cerebral palsy who often have uncontrolled body movements. Figure 3b shows a section where the subject is breathing quietly. The heated thermistor gives no explicit directional information, merely indicating a respiratory event. However, in this example of quiet breathing, the deflections caused by an expiration are lower in amplitude than inspiratory deflections since the air moving past the thermistor during an exhalation is at about 37°C. In between an expiration and an inspiration, the thermistor does not return to the true zero position as the crossover between the phases is more rapid than the thermistor can follow. At the beginning of 3b there is a swallow, with the nasal cannulae trace showing a clear apnea as the sensor has reached its true zero and this shape is characteristic of all swallows. Meanwhile, the trace from the thermistor has not quite reached its true zero flow value; this artefact during the apnea may be due to movement of the subject's head during the swallow action or the experimenter's hand. There is a brief period at the end of the traces when the subject was breathing rapidly when both transducers responded well.

Figures 4a, b illustrate the principles of using thermistors in temperature mode compared with nasal cannulae. In this example a nude thermistor was used, although he same arguments apply to the popular glass-coated versions (the difference being that the time constants will be greater for the latter). One of the nasal cannulae prongs was cut down to allow careful positioning of the nude thermistor in the naris via this shortened cannula tube. The nude thermistor was therefore measuring the same respiratory event, as it was resting in the flow stream at a similar point to the nasal cannulae prong in the other nostril.



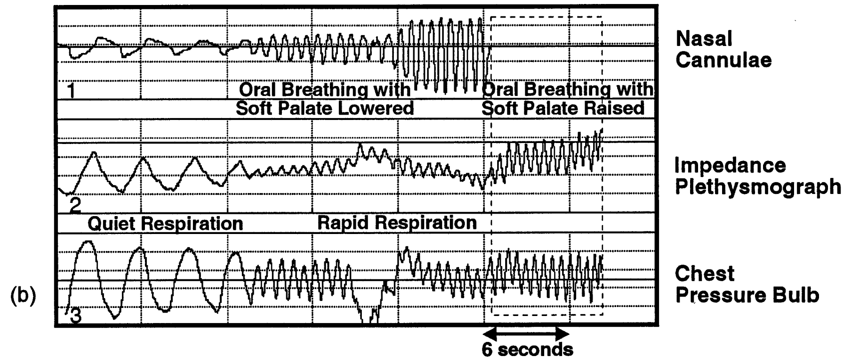


Fig. 5. Comparison of impedance plethysmography and a pressure bulb for recording chest movement. The top channels (1) represent nasal airflow via nasal cannulae, the middle channels (2) the impedance plethysmograph output, and the bottom channels (3) represent the pressure bulb signal. **(a)** Two swallow events (SA) and two episodes of breath holding. For the middle and bottom channels, an upward slope represents inspiration (Insp) and a downward slope expiration (Exp), indicated by the arrows. **(b)** A period of quiet respiration, followed by a period of oral breathing, first with the soft palate lowered and then with it raised; the dotted box shows the resulting time relationship.

Figure 4a was recorded during resting respiration with one swallow event (SA) occurring towards the end of the trace. As the subject breathes out, the resistance of the thermistor increases (and because it is operating with a constant current the voltage output also increased) and an upward deflection is recorded on the chart. The increase is initially rapid as expiration begins, with a rounding off at end expiration, signifying the time taken for the thermistor to heat up to 37°C or so. During inspiration, the thermistor detects airflow at room temperature and a falling deflection is recorded. The response time of this particular thermistor is adequate for adult resting respiration. However, after identifying the characteristic swallow apnea from the nasal cannulae trace, the response of the thermistor to the short cessation of airflow can be compared. The thermistor trace shows a change from resting respiration, but a cessation of airflow is not indicated due to the inadequate response time of thermistors used in this mode.

In Figure 4b the subject voluntarily held his breath following inspiration, with a closed airway (no cardiac artefact is visible) for a period of 12 sec or so. The point of cessation and onset of airflow is clearly shown on the nasal cannulae trace and zero flow is recorded for the duration of the apnea. The thermistor trace, however, shows a gradual rise in temperature towards body temperature (as it is close to the body) during the period of no nasal flow. The subject breathes out and then holds his breath with an open airway (the cardiac artefact is just visible on both traces) and both traces show there is no respiratory flow apart from the characteristic small fluctuations from the cardiac artefact. Presumably the thermistor has been heated to 37°C following the expiration; thereafter its temperature falls a little until the following inspiration when the normal large cooling effect is demonstrated.

Figures 5a, b, and 6 demonstrate the three main indirect methods (RIP impedance plethysmograph, and the pressure bulb) of recording respiratory information (respiratory effort) compared with the direct method employing nasal cannulae to detect the events associated with nasal flow.

At the start of the breath holding in Figure 5a the nasal cannulae trace shows an abrupt stop of airflow and the pressure bulb trace settles to zero respiratory movement approximately 2 sec later, illustrating the previ-

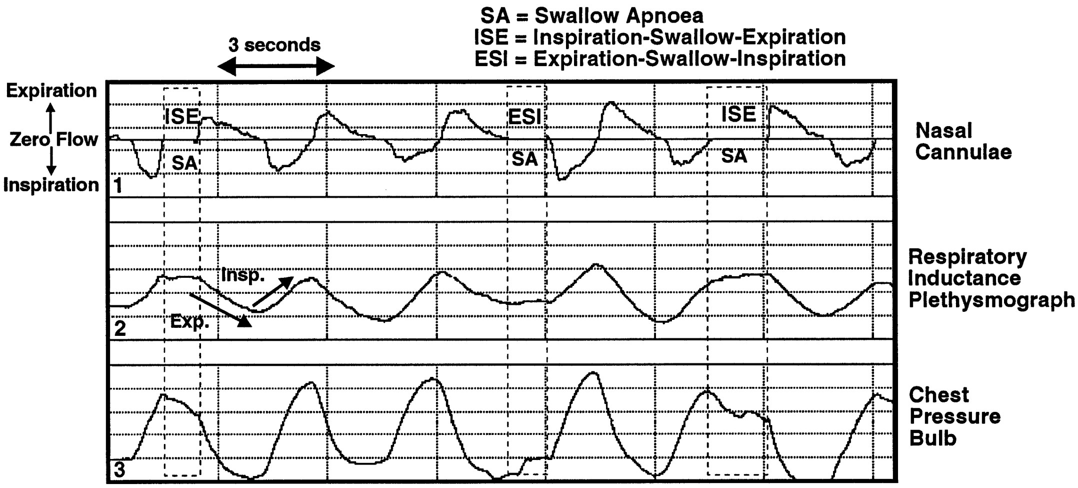


Fig. 6. An example of part of a feeding chart to illustrate the respiratory information obtained using nasal cannulae to record nasal airflow [upper channel (1)], an RIP around the chest [middle channel (2)], and a chest pressure bulb (channel 3) to record respiratory effort. There are three swallow apneas (SA) with two respiratory settings either ISE or ESI. The dotted boxes demonstrate the differing responses of the RIP and pressure bulb during the swallow apneas.

ously described effect. Hence, regular variations in pressure occurring faster than 4 Hz may not be correctly indicated by the pressure bulb, and at the point where any variation ceases there is a slow approach to the final equilibrium value. However, it may be possible too interpret the signal if these points are borne in mind.

Figures 5a and b illustrates that both the plethysmograph and the pressure bulb represent the occurrence of respiratory events well when compared with the accompanying airflow events. The cannulae signal in Figure 5a shows the most distinctive shape of a SA and the swallow events on the plethysmograph and the bulb traces are indicated as slight changes. In Figure 5b there is a period of quiet respiration and the chest movements correspond well to airflow detected at the nose. The subject then begins to pant with the soft palate lowered and the chest movements become shallower and faster. There follows a brief period where the subject closes his mouth, hence there is greater airflow at the nose. The subject who has been trained to know when he raises his soft palate does so and begins to breathe orally. No airflow at the nose is recorded but both the plethysmograph and the bulb indicate that chest movements associated with respiratory effort continue. The conclusion must therefore be that the subject is mouth breathing with the nasal passages closed by the soft palate, thus illustrating the usefulness of a secondary method of recording respiratory information.

Figure 6 shows the results when the RIP pressure bulb, and nasal cannulae are used in a feeding study of a subject taking sips of water from a cup on three occasions. It appears that the RIP and the pressure bulb are adequate indicators of respiratory information during quiet respiration, e.g., to establish rate. In this example, there are two respiratory settings [inspiration-swallow-expiration (ISE) and expiration-swallow-inspiration (ESI)] for the swallow apnea [5]. The airflow trace shows a definite and characteristic indication of the swallow event. However, the appearance of the swallow event is less obvious on both the RIP and the chest pressure bulb traces; both show a change in the respiratory movement when the swallow apnea occurs, though these are more variable and more difficult to interpret if any movement artefact is present, compared with the airflow trace.

Discussion

All the techniques described in the previous section have been used for measurement of respiration and for detection of respiratory events such as apneas (usually defined to be a cessation of breathing of 10 or more sec). Various workers have recognized that the different transducers generate signals which do not always produce agreement when registering the same event. However, the recording of the relatively rapid respiratory events during feeding have not received the same type of comparative study and this was the reason for the data presented in this paper since correct interpretation is crucial when applying these methods as a diagnostic aid. It is important that all the respiratory information before, during, and after the feed is accurate and easily extractable for the clinician.

Workers concerned with the detection of infant apneas in resting respiration have recognized the impor-

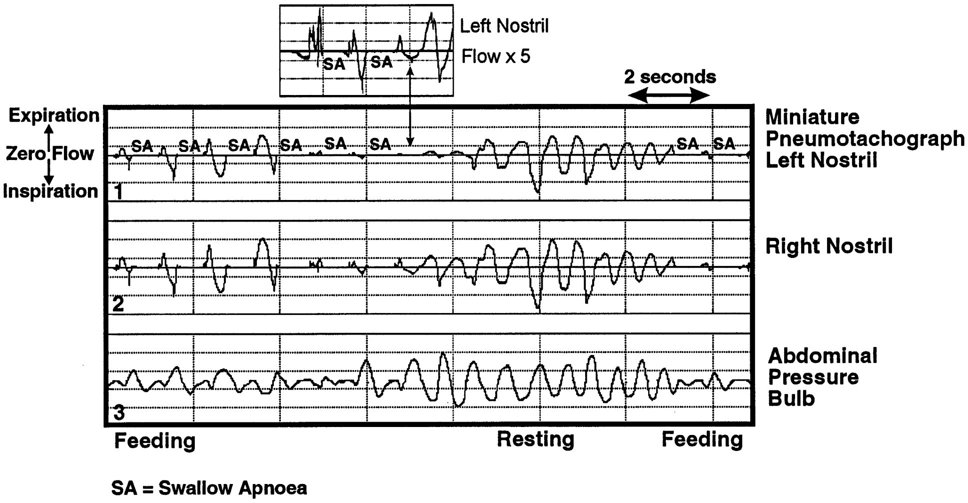


Fig. 7. An example of a mature infant respiratory feeding pattern recorded towards the middle of a breast feed. Upper and middle channels represent nasal airflow from Exeter miniaturized pneumotachographs inserted into the left and right nares, respectively; the bottom channel (3) records respiratory effort via an abdominal pressure bulb. There is a sequence of feeding swallows [each swallow event is indicated by (SA)], followed by a brief rest period before feeding is again resumed by the infant. The respiratory setting for each of the swallow apneas is ISE. Note that the apparent extension of the final apnea in the sequence of six on the left nostril trace is due to the very small signal, and the expanded (x 5) inset shows the airflow pattern matches that of the right nostril.

tance of correlating apnea detection rates generated by different techniques. Railton et al. [17] compared the clinical use of impedance monitors with Graseby bulb monitors in relation to infant resting respiration, and Upton et al. [20] detected respiratory apneas by simultaneous recording from thoracic impedance and from abdominal RIP measurements. In both studies there was a discrepancy between the respiratory information provided: in the former study there were intervals when no respiratory information was available from either transducer, whereas in the latter, out of a total of 946 apneas recorded, both transducers agreed for only 651. The present authors suggest that some of the discrepancies were due to misinterpretation of the tracts, and some disagreements in the length of apneas may be attributed to the fact that the RIP did not respond quickly enough following a large respiratory movement. By adding a mask with a Fleisch pneumotachograph to detect airflow, Upton et al. [20] also demonstrated that the discrepancies mostly occurred during mixed apneas. The failure of the impedance monitor was due to movement and technical failures and the RIP had difficulties in detecting apneic events of less than 10-sec duration. Both studies illustrate the problems of relying solely on an indirect method of recording respiration.

Cohen et al. [16] evaluated an RIP in relation to an impedance plethysmograph and a spirometer. They demonstrated that tapping the RIP produced smaller artefacts than touching the impedance electrodes; though both these devices registered artefacts from arm movements, the spirometer was immune. They also noted that during a simulated obstructive apneas (inspiratory action against a closed mouth and nasal airway), RIP signals from abdomen and chest were in antiphase. Such motions have been reported elsewhere [6] so it may be important to monitor airflow in situations where abdomen and chest make respiratory movements in antiphase to determine whether this is due to obstructive apnea or the ‘‘reverse breathing’’ reported by Rothman [21].

It is clear from the studies quoted that there are problems with instruments that attempt to record respiratory flow by indirect means, since they give information related to respiratory movements which, it should be noted, do not all give rise to useful respiratory airflow. For example, Heemels et al. [22] reported that thoracic impedance monitoring of an infant failed to record periods of obstructive apnea because of artefact due to movement and response time. The difficulties may be compounded when rapid respiratory events, such as occur in swallowing, need to be followed, especially as the act of swallowing may be accompanied by some movement of torso or an arm used in self-feeding studies.

The above studies have been quoted to illustrate the problems with the indirect transducers and act as warnings for those examining the swallowing mechanism and its coordination with respiration. Many workers studying swallowing and respiration continue to rely upon indirect methods, particularly RIP, to give precise information about a respiratory setting for a swallow, and it is hoped that the evidence provided here may suggest to them that these measurements are inadequate on their own.

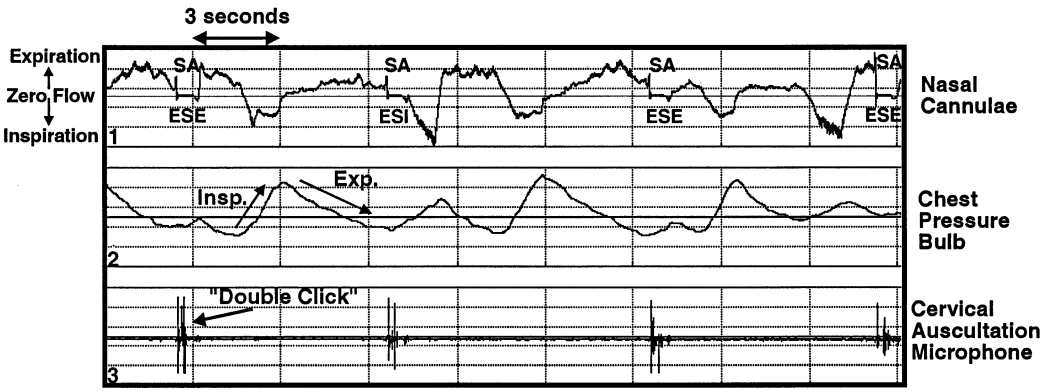


Fig. 8. An example of a chart, obtained from the EDAT equipment, of an adult sipping water from a cup. The top channel (1) represents nasal airflow recorded via nasal cannulae, the middle channel (2) represents respiratory effort recorded via a pressure bulb underneath a chest band, and the bottom channel (3) represents the signal obtained from a throat microphone during cervical auscultation of the swallows. The characteristic swallow sounds (the audible double clicks) occur during the SAs. In this example, there are two respiratory settings for the swallow apneas: ESE or ESI. In the middle trace, upward slope denotes inspiration (Insp) and downward slope expiration (Exp).

The selection of appropriate transducers and the subsequent data analysis in the study of infant feeding has been and continues to be a real clinical problem. Early workers studying feeding in babies suggested that the neonate was able to swallow without an interruption of breathing due to the high positioning of the larynx [23–25] and this is reported as fact in popular science texts [26,27]. Daniels et al. [23] studied nutritive sucking in 18 normal premature infants using strain gauges to record respiratory effort and a thermistor attached to one nostril to record nasal airflow. They did not observe a respiratory arrest and furthermore stated that the infants ‘‘could suck, swallow, and breathe simultaneously.’’

However, using nasal airflow recordings from miniaturized pneumotachographs, evidence now demonstrates that true cessation of airflow occurs for all babies during swallowing; this cessation is accompanied by a change in the pattern of respiratory movements of the chest and abdomen.

In a previous study, Selley et al. [7] identified particular infant feeding respiratory patterns—both mature and immature. The most common respiratory setting for a mature infant swallow during feeding was reported to be ISE, with the swallow always accompanied by a short period of zero nasal airflow, a true respiratory arrest, since the oral port was blocked by the teat or nipple. A research program has recently been completed which investigated in detail the maturing pattern of breast and bottle feeding in healthy term and premature babies [11–13]. A total of 61 normal term infants, 71 normal premature infants, and 47 infants, referred by clinicians to the investigators for assessment, were studied. All the infants showed a period of zero nasal flow during each swallow.

Figure 7 is taken from a term infant who is breast feeding and displaying a mature and coordinated pattern. Two miniaturized pneumotachographs were inserted so that the respiratory airflow from each nostril was recorded separately. A Graseby pressure bulb was placed over the anterolateral thoraco-abdominal junction (where the maximum movement occurs), to record respiratory effort. This diagram clearly illustrates that during a swallow (identified using cervical auscultation) there is a short apnea as illustrated by both of the airflow traces. It should be noted that the airflow is identical in shape from each nostril but the distribution of flow is slightly different, the left nostril carrying the smaller flow (see x 5 expansion in the inset to the figure).

Although the immature pattern identified by Hanlon et al. [11,13] differs from the mature pattern illustrated here, no infant was identified as being able to ‘‘suck, swallow and breathe simultaneously’’ [23]; although sucking normally occurs simultaneously with breathing, swallowing does not. Perhaps one way of describing a perfectly coordinated cycle is to use the popular phrase 1:1:1 pattern [28], i.e., one breath, one suck, one swallow, realizing that these are not sequential but that sucking and breathing occur simultaneously. Respiratory airflow is always interrupted for the swallow. The present authors would suggest that the failure of Daniels et al. [23] to identify a respiratory arrest was due to the poor response time of the thermistor employed. Unfortunately, no technical description was supplied by Daniels et al. but evidence is presented here of long response times for thermistors used in the thermometry mode.

Bu’Lock et al. [28] described a normal coordinated feeding cycle as one in which ‘‘breathing is interpolated between swallows, but goes on to say that ‘‘breathing appears to be continuous and uninterrupted,’’ which may be confusing for readers. It is important to distinguish between movement associated with breathing or attempts at breathing and breathing flow. Bu'Lock et al. employed a Graseby pressure bulb to record respiratory effort. By referring to the respiratory effort trace shown in Figure 7, two distinct patterns of behavior are evident. The first is seen during resting respiration and the second during feeding. For the rest period, the pressure bulb trace is as expected, showing an upward slope for inspiration and a downward slop for expiration. The bulb trace during feeding demonstrates that this relationship holds during the respiratory excursions between swallow apneas (the inspiration before and the expiration after) but deflections continue during the period of zero nasal flow. Although an alteration in shape and amplitude occurs during the interval of zero airflow, these signals should not be interpreted as uninterrupted breathing nor demonstrating actual airflow but only changes in abdominal dimension (perhaps even the so-called swallow breath [1]). Bu'Lock et al. further state that ''less well co-ordinated feeding, breathing is always interrupted by swallowing.'' This immature feeding pattern, where infants show prolonged apnea associated with multiple swallowing (described by Hanlon et al. as multiple swallow apneas) and where breathing movements cease for many seconds would give time for the bulb to recover and register the apnea.

As a final examples, Figure 8 is a typical feeding chart obtained during an Exeter Dysphagia Assessment Technique (EDAT) [5] experiment using the chosen transducers and is taken from a normal 24-year-old male while sipping water from a cup. Channel 1 shows the pressure changes associated with nasal respiration as detected by the nasal cannulae and the pressure transducer. The swallow apneas (three of ESE type and 1 ESI) have a characteristic appearance with an abrupt stop of airflow at the start of the apnea and a sharp onset of airflow following the apnea. The sharp airflow spikes at the start and end of the swallow apnea are commonly observed in swallow events. The ESI event is unusual in that the majority of swallow apneas in normal adults are followed by expiration. Indeed, in this particular subject 29/30 (97%), swallows studied were ESE type and there was only one ESI event. Channel 2 shows respiratory effort recorded by a pressure bulb underneath a chest band and demonstrates again that timing information for the swallow event would be difficult if this channel was used in isolation. Channel 3 shows the signal obtained by cervical auscultation [29] while the subject is swallowing and the ''double click,'' clearly audible in a normal swallow, is assumed to be represented by the double spike on the trace. This combination of transducers has been successfully used on both normal and abnormal subject groups to provide some useful clinical information and is recommended to others for the study of the coordination between respiration and swallowing.

The above discussion shows that attention has been paid to interpreting data from different transducers during resting respiration and during feeding studies in infants. In the case of similar studies on normal and dysphagic children and adults, the lack of comparative studies has led to the present investigation. Various combinations of transducers have been tried on the following subject groups: children with cerebral palsy, normal children, normal adults, subjects with Rett syndrome (Morton RE, personal communication), stroke patients, and a small number of patients with other neurological swallowing problems. It is hoped in the near future to compare results from the Exeter group with those obtained by other workers on similar subject groups, in particular, work on cerebral palsy children, where other transducers have been employed.

Conclusion

Respiratory studies both at rest and during feeding provide valuable information in aiding the diagnosis and treatment of dysphagic patients. The instrumentation for recording respiratory information accurately in a noninvasive manner has been discussed here with a view to helping clinicians understand what is being recorded by their transducers. Many methods have been investigated in both the laboratory and on different subject groups for respiration assessments while resting and during feeding and it has been demonstrated that a number of the transducers, although perfectly adequate for respiration monitoring in apnea studies, are less clinically useful in feeding either because of inadequate response time or movement artefact. Nasal airflow devices are the most suitable, but even these need some supplementation, e.g., to distinguish mouth breathing with occlusion of the nasal airway from central and/or obstructive apneas.

It is important to appreciate the nature of the signals generated during swallowing events and to distinguish them from artefacts. It is also important to recognize that the ''respiratory setting'' of a swallow can be variable, i.e. expiration-swallow-expiration/inspiration (ESE, ESI) inspiration-swallow-expiration/inspiration (ISE, ISI). Therefore, the transducer may give different signals for these depending to some extent on the response speed and on the placement of the transducers.

The following combinations of transducers have been successfully used in the authors' work. When studying infants, one miniaturized Exeter pneumotachograph records the events of nasal airflow. Two pneumotachographs are employed when quantitative flow information is required, but often this is unnecessary. If pneumotachographs are not available then infant nasal cannulae connected to the pressure transducer may be a sufficient substitute to record the events of nasal respiration. A simple, abdominal pressure bulb may be taped to the skin in order to monitor respiratory effort; this is particularly important when studying apnea in premature babies and in feeding studies.

In normal adults and children, nasal cannulae are used to monitor respiratory airflow and this is usually sufficient as relatively few are mouth breathers. When quantitative information is clinically desirable, scaled miniaturized pneumotachographs may be employed. As stated earlier, supplementation of nasal airflow by respiratory effort data is essential in swallowing investigations, especially for studies of dysphagic subjects. This additional information is necessary when investigating respiratory state in patients with neurological disorders, e.g., Rett syndrome and cerebral palsy, where occasional oral respiration with a raised soft palate produces zero nasal flow which, without this additional information, could be interpreted as an apnea. One or two pressure bulbs held in position by tape or elasticized belts at low tension may be used as indicators of respiratory effort. Measurement of actual airflow still remains the most useful indicator of respiration during the swallowing action.

As a result of this experience, the authors have been led to the use of nasal airflow along with chest and/or abdominal respiratory movements as the best combination for swallowing and respiration studies. The transducers suggested here provide sufficient detail for most events that occur during resting and feeding respiration to be interpreted unequivocally. They are relatively easy to apply and adjust to different sizes and condition of the subject or patient and they are also acceptable to patient and caregiver; thus the instrumentation can be used for research as well as for clinical diagnostic purposes. The transducer combination is relatively cheap and readily available on the market except for the miniaturized pneumotachograph which is not difficult to manufacture if access to a small lathe is available. A combination of the transducers, called the Exeter Dysphagia Assessment Technique (EDAT), incorporating these recommended devices, has been used in Exeter by clinical groups over many years to study hundreds of subjects over a wide age range, and several other research centers are also finding them useful.

In the authors opinion the equipment described in this section is the most acceptable, minimally invasive, and most practical to use while providing useful information. However, the measurements rely upon correct application of the devices, careful interpretation of the data, and some cooperation from the subjects themselves. It is almost inevitable that in some cases inadequate information will be gleaned from the test due either to the instrumentation and/or the subject. Ideally, many other measurements supplying extra information may be desirable but there has to be a compromise between the minimum necessary, practicality, and patient acceptability.

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References

1. Wilson SL, Thach BT, Brouillette RT, Abu-Osba YK: Coordination of breathing and swallowing in human infants. *J App Physiol 50:*851–857, 1981
2. Martin BJW, Logemann JA, Shaker R, Dodds WJ: Coordination between respiration and swallowing: respiratory phase relationships and temporal integration. *J App Physiol 76:*714–723, 1994
3. Upton CJ, Milner AD, Stokes GM: Upper airway patency during apnoea of prematurity. *Arch Dis Child 67:*419–424, 1992
4. Mathew OP, Roberts JL, Thach BT: Pharyngeal airway obstruction in preterm infants during mixed and obstructive apnea. *J Pediatr 100:*964–968, 1982
5. Selley WG, Flack FC, Ellis RE, Brooks WA: The Exeter Dysphagia Assessment Technique. *Dysphagia 4:*227–235, 1990
6. Elwell CE: Measurements in the diagnosis and treatment evaluation of obstructive sleep apnea. MPhil Thesis, University of Exeter, Exeter, UK 1991
7. Selley WG, Ellis RE, Flack FC, Brooks WA: Co-ordination of sucking, swallowing and breathing in the newborn: its relationship to infant feeding and normal development. *Br J Disord Commun 25:*311–327, 1990
8. Ellis RE, Flack FC, Curle HJ, Selley WG: A system for the assessment of nasal airflow during speech. *Br J Disord Commun 13:*31–40, 1978
9. Fleisch A: Pneumotachograph: apparatus for recording respiratory flow. *Arch Ges Physiol 209:*713–722, 1925
10. Sullivan WJ, Peters GM, Enright PL: Pneumotachographs: theory and clinical application. *Respiratory Care 29:*736–749, 1984
11. Hanlon MB, Shoesmith H, Selley W, Flack F, Ellis R, Tripp JH: Breast feeding in preterm infants: maturation of deglutition apnea. *Conf Report Pediatr Pulmonol 16:*392, 1993
12. Shoesmith HJ: Instrumentation for the study of infant feeding. MPhil Thesis, University of Exeter, Exeter, UK 1993
13. Hanlon M, Shoesmith H, Selley W, Flack F, Ellis R, Tripp J: The relationship between swallowing and breathing in normal preterm and term infants [Abstract]. London: Scope Meeting, 1995
14. Brouillette RT, Thach BT: A self-retaining flowmeter for preterm infants. *J Appl Physiol 48:*569–571, 1980
15. Tarrant SC: Instrumentation for the study of respiration at rest and during feeding. MPhil Thesis, University of Exeter, Exeter, UK 1995
16. Cohen KP, Panescu D, Booske JH, Webster JG, Tompkins WJ: Design of an inductive plethysmograph for ventilation measurement. *Physiol Meas 15:*217–229, 1994

17. Railton R, Fisher J, Mitchell I, Barclay RPC: Long-term respiration monitoring in infants—a comparison of impedance and pressure capsule monitors. *Clin Phys Physiol Meas 4:*91–94, 1983
18. Primiano FP: Measurement of flow and volume of blood. In: Webster (ed.): *Medical Instrumentation Application and Design,* 2nd ed. Boston: Houghton Mifflin, 1992, pp 444–445
19. Selley WG, Ellis RE, Flack FC, Bayliss CR, Pearce VR: The synchronization of respiration and swallow sounds with videofluoroscopy during swallowing. *Dysphagia 9:*162–167, 1994
20. Upton CJ, Milner AD, Stokes GM: Combined impedance and inductance for the detection of apnea of prematurity. *Early Hum Dev 24:*55–63, 1990
21. Rothman JG: Effects of respiratory exercises on the vital capacity and forced expiratory volume in children with cerebral palsy. *Phys Ther 58:*421–425, 1978
22. Heemels JP, Ros HH, Sipkema P, de Vries F: Tracheal sound detector. *Med Biol Eng Comp 24:*182–185, 1986
23. Daniels H, Casaer P, Devlieger H, Eggermont E: Mechanisms of feeding efficiency in preterm infants. *J Pediatr Gastroenterol Nutr 5:*593–596, 1986
24. Peiper A: Cerebral function in infancy and childhood, 3rd ed., New York: Pitman Medical Publishing, 1963
25. Crelin ES: *Functional Anatomy of the Newborn.* New Haven, CT: Yale University Press, 1973
26. Leakey R: *The Origin of Humankind.* London: Weidenfeld and Nicolson, 1994
27. Sporik: Why block a small hole? The adverse effects of nasogastric tubes. *Arch Dis Child 71:*393–394, 1994
28. Bu'Lock F, Woolridge MW, Baum JD: Development of co-ordination of sucking, swallowing and breathing: ultrasound study of term and preterm infants. *Dev Med Child Neurol 32:*669–678, 1990
29. Vice FL, Heinz JM, Giuriati G, Hood M, Bosma JF: Cervical auscultation of suckle feeding in newborn infants. *Dev Med Child Neurol 32:*760–768, 1990
30. Bendixen HH, Smith GM, Mead J: Pattern of ventilation in young adults. *J App Physiol 19:*195–198, 1964
31. Eccles R: The central rhythm of the nasal cycle. *Acta Otol 86:*464–468, 1977
32. Issa EG, Porostocky S: Effect of continuous swallowing on respiration. *Resp Physiol 95:*181–193, 1994
33. Selley WG, Flack FC, Ellis RE, Brooks WA: Respiratory patterns associated with swallowing: part 1. The normal adult pattern and changes with age. *Age Ageing 18:*168–172, 1989
34. Bjure J, Berg K: Effect of physical training on school children with cerebral palsy. *Acta Paediatr Scand* (Suppl) *204:*35–39, 1970
35. Davis R, Gray E, Ryan T, Shukman J: Bioengineering changes in spastic cerebral palsy groups following cerebellar stimulation. *App Neurophysiol 48:*111–116, 1985
36. Koheil R, Sochaniwskyj A, Bablich K, Ross D: Monitoring respiration and its co-ordination with swallowing in children with cerebral palsy by means of respiratory inductance plethysmography [Abstract]. *Dev Med Child Neurol Meeting 28:*37–38, 1986
37. Kotagal S, Gibbons VP, Stith JA: Sleep abnormalities in patients with severe cerebral palsy. *Dev Med Child Neurol 36:*304–311, 1994
38. McPherson KA, Kenny DJ, Koheil R, Bablich K, Scohaniwskyj A, Milner M: Ventilation and swallowing interactions of normal children and children with cerebral palsy. *Dev Med Child Neurol 34:*577–588, 1992
39. Miyasaka K, Hoffman HJ, Froese AB: The influence of chronic cerebellar stimulation on respiratory muscle co-ordination in a patient with cerebral palsy. *Neurosurgery 2:*262–265, 1978
40. Parrott LC, Selley WG, Brooks WA, Lethbridge PC, Cole JJ, Flack FC, Ellis RE, Tripp JH: Dysphagia in cerebral palsy: a comparative study of the Exeter Dysphagia Assessment Technique and a multidisciplinary assessment. *Dysphagia 7:*209–219, 1992
41. Reid DT, Sochaniwskyj A: Effects of anterior-tipped seating on respiratory function of normal children and children with cerebral palsy. *Int J Rehabil Res 14:*203–212, 1991
42. Bamford O, Taciak V, Gewolb IH: The relationship between rhythmic swallowing and breathing during suckle feeding in term neonates. *Pediatr Res 31:*619–624, 1992
43. Weber F, Woolridge MW, Baum JD: An ultrasonographic study of the organisation of sucking and swallowing by newborn infants. *Dev Med Child Neurol 28:*19–24, 1986
44. Casaer P, Devilieger H, Willekens H, Daniels H, Dereymaeker H, Vital-Durnad G, Eggermont E: Recording of upper and lower thoracic and abdominal respiratory movements in preterm neonates: an improved method. *Acta Paediatr Belg 33:*253–260, 1980
45. Dreier T, Wolff PH, Eager Cross E, Cochran WD: Patterns of breath intervals during non-nutritive sucking in full-term and ''at risk'' preterm infants with normal neurological examinations. *Early Human Dev 3:*187–199, 1979
46. Johnson P, Salisbury DM: Breathing and sucking during feeding in the newborn. *Parent-Infant Interaction.* Amsterdam: CIBA Foundation Symposium 33, New Series, ASP, 1975
47. Kerbl R, Kenner T, Haidmayer R, Kerschhaggl P, Kurz R: Co-ordination of sucking, swallowing and respiration in infants with sleep apnea syndrome. *Biomedizinische Technik 29:*274–278, 1984
48. Mathew OP, Clark ML, Pronske ML, Luna-Solarzano HG, Peterson MD: Breathing pattern and ventilation during oral feeding in term newborn infants. *J Pediatr 106:*810–813, 1985
49. Milner AD, Saunders RA, Hopkin IE: Apnea induced by airflow obstruction. *Arch Dis Child 52:*379–382, 1977
50. Paludetto R, Robertson SS, Martin RJ: Interaction between non-nutritive sucking and respiration in preterm infants. *Biol Neonate 49:*198–203, 1986
51. Ruggins NR, Milner AD: Site of airway obstruction in preterm infants with problematical apnea. *Arch Dis Child 66:*787–792, 1991
52. Russell G, Feather EA: Effects of feeding on respiratory mechanics of healthy newborn infants. *Arch Dis Child 45:*325–327, 1970
53. Martin RJ, Siner B, Carlo WA, Lough M, Miller MJ: Effect of head position on distribution of nasal airflow in preterm infants. *J Pediatr 112:*99–103, 1988