A new tool for measuring the suckling stimulus during breastfeeding in humans: the orokinetogram and the Fourier series

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The Fourier series was used to analyse the oral movements recorded by the orokinetogram during breastfeeding in human babies. This is a new method that allows recording of oral movements without introducing any extrinsic element between the nipple and the mouth of the baby. The advantage of displaying sucking activity after fast Fourier transform (FFT) is that this algorithm allows storage, quantification and frequency analysis of the oral movements throughout a sucking bout, which enables the total oral activity to be measured. Two types of oral movements are found: slow high amplitude (SHA) and fast low amplitude (FLA). FLA movements may be derived from peristaltic movements of the tongue that result in tickling stimuli to the mechanoreceptors of the nipple and milk expression. The frequency bandwidth of oral movements is wider (0–8 Hz) than has been described previously (0–3 Hz) and this is due to the presence of the FLA oral movements. An indirect measurement of the energy of oral movements during sucking is obtained by the pattern of energy distribution used in each individual frequency band by oral movements. This pattern changes in relation to the periods of continuous and intermittent sucking activity. SHA and FLA oral movements are more intense during continuous sucking. Statistical analysis showed a correlation between the energy of SHA and FLA waves throughout the sucking bout, and also that the highest level of energy during sucking activity is displayed during the first 2 min. The novel tools described in this paper allow investigation of the role of sucking stimulus in reflex hormone release and other mother–infant interactions.

Introduction

During breastfeeding, a baby obtains nourishment and at the same time induces reflex hormonal changes in the mother which bring about milk production and postpartum amenorrhoea (Howie et al., 1982; Diaz et al., 1988; Yokoyama et al., 1994). The stimulus of suckling is composed of a series of oral movements that both draw the milk out of the lactiferous sinuses and stimulate nipple mechanoreceptors, which in turn trigger reflexes resulting in the release or inhibition of hormones in the mother.

The oral movements of babies during suckling have been thoroughly investigated (Wolff, 1968; Dreweet and Wooldridge, 1979). However, to date, only partial measurements of the magnitude of sucking movements have been determined because the amplitude and frequency of oral movements have not been quantified simultaneously throughout an entire sucking bout. It is important to determine the overall magnitude of this stimulus to explore the reflex action of sucking during breastfeeding and it is necessary to consider three dimensions: amplitude, frequency and period of sucking. It is possible to quantify and analyse the oral movements throughout the entire sucking bout by means of the Fourier series. The advantage of displaying sucking activity in the frequency domain after FFT is that this algorithm allows storage, quantification and frequency analysis of all the periodical waves produced by oral movements throughout a sucking bout, enabling measurement of the total oral activity. Therefore, it is possible to quantify and statistically analyse the overall magnitude of the sucking stimulus in breastfed babies. In this study, the oral movements of breastfed babies during sucking bouts were recorded using the orokinetogram, a novel method that allows recording of high and low amplitude movements without introducing any extrinsic element between the nipple and the baby’s mouth.

Materials and Methods

Subjects

A total of 30 healthy breastfed babies aged between 1 and 2 months with a fasting period of no less than 3 h were
The babies were divided into two groups. Pressure transducer and orokinogram recordings were taken simultaneously from one group of ten babies. In the second group of 20 babies, only the orokinogram was used. The data of the waveforms produced by oral movements were statistically analysed in six babies from the second group during a 4–6 min suckling bout without arrest. Oral movements during the suckling bout were recorded from the moment the infants were attached to the nipple until their spontaneous detachment. Infants were correctly positioned and attached to the breast during breastfeeding. Babies were weighed before and after the suckling period with an electronic digital balance to an accuracy of 0.1 g. A few babies were excluded from the study because their body weight did not increase after the suckling period. These babies did not readily attach to the nipple and had short periods of sucking. It is possible that these babies had not been fasted for the specified 3 h.

Mothers were aged between 20 and 25 years with normal nutrition. The research protocol was approved by the Hospital General de Agudos Dr Carlos G. Durand ethical committee. All the mothers received appropriate information and signed a consent form before entering the study.

Orokinogram

Two recording electrodes were placed on each infant: the first was attached to the chin near the lower lip on the skin covering the bone of the lower jaw; the second was placed between the first electrode and the hyoid bone on the skin covering the muscles of the tongue. A ground electrode was placed on the baby’s forehead. Electrodes were held in place by means of sparadrap tape (Micropore 3M). Oral movements produced variations in the electrical resistance of the skin between the two recording electrodes, which was amplified and recorded (Akonic Polygraph, Argentina).

Intra-oral pressure

A Silastic catheter (Dow Corning, Midland, MI) was filled with sterile water and fixed by means of sparadrap tape to the external side of the breast so that its free end was at the level of the nipple. The free end of the catheter was closed so that it recorded only positive pressure exerted on the nipple during sucking activity. During suckling, the babies held the nipple and the catheter together. The other end of the catheter was connected to a Statham PB-23 pressure transducer, and the signals obtained were amplified.

Orokinogram and pressure transducer recordings

Simultaneous orokinogram and pressure transducer recordings were obtained to enable comparisons to be made.

Digitalization and analysis of the signals

Signals obtained by the orokinogram and pressure transducer recordings were digitalized by means of a Keithel DAS 1601 analog/digital I/O board. Signals were recorded, analysed and stored magnetically. The FFT algorithms were used to analyse the periodical wave signals produced by oral movements during suckling. Oral movements were analysed in frames of 30 s of sucking. When a pressure transducer records high and low intensity signals, the high intensity signals may saturate because of the high gain used to detect the low intensity signals. The orokinogram simultaneously recorded high and low amplitude signals without saturation. These recordings were used to analyse the oral movements because saturated signals are unsuitable for analysis with the Fourier series.

The three-dimensional pattern of energy in terms of frequency of oral movements during sucking

The autopower spectral density (APSD) function was used to analyse in three dimensions the amplitude and frequency of oral movements and their variations throughout the sucking bout. The APSD function uses the signals after autocorrelation and calculates the normalized power of each individual frequency channel from the amplitude spectrum that is output by the FFT algorithm. It shows the power in each frequency band and represents the distribution of energy in terms of frequency (Ramirez, 1985). The power of each frequency channel is proportional to the amplitude and to the number of the periodical oral movements that matches the frequency channel. Therefore, the APSD is an indirect measurement of the energy used by the oral movements in each one of the different frequencies displayed. The APSD unit is V^2 Hz.

Statistical analysis

The following measurements were determined in a group of six babies that were fed during a 4–6 min suckling bout, without detachment from the nipple.

Total amount of power displayed in the distribution of energy in terms of frequency throughout the sucking bout. The area under the curve of the APSD represents the total amount of power displayed in the distribution of energy in terms of frequency. The area under the curve of each consecutive APSD frame of 30 s throughout the whole sucking period was calculated to determine the amount of energy displayed in each frame. The amount of the energy was measured in arbitrary units. The maximum energy was considered to be 100%, and the energies of other frames were calculated as a proportion of the maximum throughout the sucking bout. Means ± SEM from the area under the curve of each one of the successive APSD frames of all babies were calculated. The presence of linear component trends in the data was checked by means of tests for the homogeneity of individual longitudinal regression lines, accounting for intra- and inter-subject variability (Crowder and Hand, 1990).

Temporal relationships between slow and fast oral movements throughout the sucking bout. In each frame of 30 s, averages
of APSD data were separately calculated for SHA and FLA frequency channels. Statistical regression and correlation between FLA and SHA averages throughout the entire suckling bout were calculated for each baby.

Results

Simultaneous recordings of oral movements obtained by the orokinogram and by the pressure transducer at the level of the nipple were similar (Fig. 1). SHA and FLA oral movements were observed using both methods; the FLA movements were mainly superimposed on the SHA movements. When the orokinogram was used, recordings of both SHA and FLA oral movements were easily detected, whereas with the pressure transducer, FLA oral movements could only be detected after a high gain, which can cause saturation of the signal. With both recording systems, the display of SHA and FLA movements was consistent within infants provided that the signals from the pressure transducer did not saturate. When this happened, only SHA movements were consistently observed. Continuous and intermittent periods of suckling activity were observed with both recording methods.

The waveforms from the oral movements can be displayed in time (Fig. 2a) and frequency domain (Fig. 2b). Oral movements displayed in frequency after FFT or time domains are indistinct, as once the FFT is transformed back to the time domain by the inverse fast Fourier transform (IFFT) algorithm (Fig. 2c), the result is similar to that displayed by the time domain.

Continuous and intermittent periods of suckling activity can be displayed in time and frequency domains (Fig. 3a,b). The orokinogram traces and the distribution of energy in terms of frequency changes throughout the suckling bout in relation to the periods of continuous or intermittent suckling. SHA oral movements under 1 Hz predominate during continuous suckling and shift to a higher frequency during

Fig. 1. Simultaneous recording of oral movements of breastfeeding human babies using a pressure transducer (—) and an orokinogram (—). Arrows show fast low amplitude oral movements that are superimposed on slow high amplitude oral movements. These two types of oral movement are concurrently displayed by the orokinogram and by the transducer which detects positive pressure at the level of the nipple.

Fig. 2. The waveforms from oral movements of breastfeeding human babies displayed in (a) time domain, (b) frequency domain after fast Fourier transform (FFT), and (c) back to time domain by inverse fast Fourier transform. Once FFT is transformed back to the time domain by the inverse FFT algorithm, the result is similar to that for the time domain (a).
Fig. 3. Samples (25 s) of (a) continuous and (b) intermittent periods of suckling activity in breastfed human babies. In each sample, the oral movements are displayed in time (upper trace) and in frequency domain at which slow high amplitude (SHA) (left lower trace) and fast low amplitude (FLA) (right lower trace) channels are shown. SHA and FLA movements are more intense during continuous suckling. SHA movements under 1 Hz predominate during continuous suckling. During intermittent suckling, movements of a higher frequency prevail.

intermittent suckling. SHA and FLA oral movements are more intense during continuous suckling.

The distribution of energy in terms of frequency in the oral movements displayed in three dimensions during whole suckling bouts was recorded (Fig. 4). This was the amount of energy used in each frequency band in 30 s frames during a complete suckling bout, from the time the infant attached to the nipple until spontaneous detachment. The bandwidth of the periodic oral movements displayed during suckling varied in a scale ranging from 0 to 8 Hz (Fig. 4). The same bandwidth was observed during the whole suckling bout. The pattern of energy used in each one of the frequencies that were displayed by periodical oral movements changed during the suckling bout. The pattern of energy of the SHA movements (Fig. 4a) showed that those of the lowest frequency, that is less than 1 Hz, used higher energy levels during the first few minutes of recording. After the first few minutes, higher energy levels shifted towards oral movements of higher frequencies. The pattern of energy of the FLA movements (Fig. 4b) was similar to that described for the SHA movements, but the energy was 100 times lower. The means ± SEM of the total amount of power displayed in the distribution of energy in terms of frequency throughout the whole suckling bout was calculated in a group of six babies (Fig. 5). Statistical variation was observed between individual regressions. This variation accounts for 21.4% of the total variation in the data. However, there was a linear trend of energy that was similar for the whole group (P < 0.001). The highest level of energy was displayed during the first 2 min of the suckling bout, after which the energy decreased with fluctuations. The variation observed between babies may be due to asynchronies in the periods of continuous or intermittent suckling activity.

Statistical analysis performed in individual babies showed a correlation between the energy of SHA and FLA waves during a suckling bout (P < 0.001). No individual variation was found in slope or in y intercepts between the data for each baby (Fig. 6).
quantified and analysed in the frequency domain after FFT. This is the first study to reveal that the frequency bandwidth of these oral movements is wider (0–8 Hz) than previously reported by Drewet and Wooldridge (1979) (0–3 Hz). This is due to the presence of FLA movements. The same bandwidth of frequencies is observed throughout the whole suckling bout. These data are in agreement with those of Bowen Jones et al. (1982), who reported that the frequency distribution of oral movements is unimodal.

During breastfeeding, babies obtain the milk contained in the lactiferous sinuses (Wooldridge, 1986; Lau et al., 1997). Positive pressure on the nipple from the surface of the tongue is the primary force that evacuates the milk. A roller like peristaltic wave of contraction throughout the surface of the tongue squeezes milk from the ampullae into the oesophagus (Gwynne-Evans, 1951; Ardran et al., 1958; Wooldridge, 1986). Simultaneous recordings from an orokinetogram and a pressure transducer showed that both the SHA and the FLA oral movements recorded by the orokinetogram exert a positive pressure action upon the nipple because they are concurrently detected at the same amplitude by the pressure transducer, which only records positive pressure. The positive pressure at the nipple was considered to represent the component of suckling that corresponds to the squeezing of the nipple (Lau et al., 1997). Therefore, it is possible that the waves recorded by the orokinetogram represent oral activity associated with nipple squeezing. The relationship between SHA movements (0–3 Hz) and milk ingestion has been studied (Wolff, 1968; Drewet and Wooldridge, 1979). The FLA movements (4–8 Hz) described for the first time in this paper are superimposed on the SHA movements. This vibrating type

**Discussion**

Oral movements during a suckling bout in babies of 30–60 days of age were recorded using an orokinetogram and were measured throughout the whole suckling bout of six breastfeeding human babies. Data are expressed in arbitrary units. Values are means ± SEM. The presence of linear component trends in the data was checked, accounting for intra- and inter-subject variability. Despite variation, there is a linear trend of energy that is similar for the whole group \((P < 0.001)\). The highest level of energy was displayed during the first 2 min, after which the energy decreased.

**Fig. 5**. The total amount of power displayed in the distribution of energy in terms of frequency throughout the whole suckling bout of six breastfeeding human babies. Data are expressed in arbitrary units. The intercepts throughout the whole suckling bout are checked, accounting for intra- and inter-subject variability. Despite variation, there is a linear trend of energy that is similar for the whole group \((P < 0.001)\). The highest level of energy was displayed during the first 2 min, after which the energy decreased.

**Fig. 6**. Correlation \((P < 0.001)\) between the energy of slow high amplitude (SHA) and fast low amplitude (FLA) waves throughout a suckling bout in breastfeeding human babies. No individual variation was found in the slope or the \(y\) intercepts in the data for each baby.
of movement may give a tickling stimulus to mechanoreceptors in the nipple and areola due to its high speed and low intensity. Moreover, FLA movements may derive from peristaltic movements of the tongue related to the expression of milk from the nipple. They may propel milk and stimulate mechanoreceptors in the nipple and areola to release hypophysical hormones.

Sampled waveform data may be indistinctly displayed in time or frequency domain. The advantage of displaying the waveforms after FFT is that this algorithm allows storage, quantification and frequency analysis of all the periodical waveforms produced by oral movements throughout the suckling bout, enabling the total oral activity to be measured. The pattern of the distribution of energy in terms of frequency changes in relation with the continuous and intermittent periods of suckling. Throughout the suckling bout, the pattern of SHA movements showed that those of the lowest frequency (under 1 Hz) are predominant during the first few minutes of suckling, after which those of higher frequency are most common (about 2 Hz). Movements of 1 Hz correspond to continuous suckling episodes, while those of 2–3 Hz correspond to intermittent episodes. It has been reported that milk ingestion occurs mainly during episodes of continuous suckling (Wolf, 1968). The pattern of FLA movements observed in the present study showed that these movements are more intense during continuous suckling. The energy displayed by the FLA movements is 100 times lower than the SHA movements. However, the pattern is similar, since the slowest movements of this group are predominantly at the beginning of the suckling bout. Statistical analysis performed in six babies showed that despite variations between individual regressions, there was a similar linear trend of energy in the group. The highest levels of energy were displayed during the first 2 min of the sucking bout and declined thereafter. These results are in accordance with the findings of Prieto et al. (1996), who reported a gradual decrease of suckling activity throughout the suckling bout. This may be explained by the fact that babies obtain the most milk during the first 2 min of suckling, as reported by Lucas et al. (1979). Statistical analysis also showed a correlation between the energy of the SHA and FLA waves throughout the suckling bout. The energy of the SHA and FLA waves increased or decreased simultaneously. If it is assumed that the FLA waves represent peristaltic waves of contraction of the tongue, this type of rapid tongue movement would predominate during continuous sucking episodes in which mainly SHA oral movements occur. Therefore, the peristaltic contraction activity of the tongue would be greater and the stimulation of mechanoreceptors in the nipple caused by this type of rapid movement would be more intense during nutritive sucking episodes.

Oral movements stimulate mechanoreceptors in the nipple which in turn evoke a pattern of nerve action potentials in the mammary nerve (Voloschin et al., 1988). Therefore, it may be assumed that the pattern of the distribution of energy in terms of frequency displayed by oral movements represents the sensorial code used by the infant to induce hormonal changes in the mother. It is important to quantify this stimulus to explore the hormonal reflex action of suckling.

In conclusion, the results obtained in this study show that the Fourier series is useful for measuring the total oral activity during a sucking bout and, consequently, quantifying and statistically analysing the overall magnitude of the sucking stimulus. Use of the Fourier series and the orokinogram allows novel investigation of the relationship between the overall magnitude of suckling and the reflex release of hormones.

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