Uterine electromyography: A critical review

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On the basis of a literature review, this work summarizes uterine animal and human electromyographic information obtained at cellular, myometrial, and abdominal levels during gestation and parturition. We show that both internal and external electromyograms occur in phase with intrauterine pressure increase and exhibit similar spectra, including a slow wave (0.01 < frequency < 0.03 Hz) probably because of mechanical artifacts and a fast wave whose frequency content can be subdivided into a low-frequency band always present in every contraction and a high-frequency band related to efficient parturition contractions. Application of classic spectral techniques to electromyogram envelopes has identified group propagation but not pacemaker areas. However, no time delay or classic propagation has been demonstrated by applying the same spectral techniques to the electromyogram itself, probably because of the nonlinearity and three-dimensional nature of the propagating process. (Am J Obstet Gynecol 1993;169:1636-53.)

Key words: Uterine activity, electromyography, propagation, spectral analysis

During the last 50 years uterine electromyograms have been extensively investigated. They have been recorded either internally with endouterine electrodes or externally with abdominal electrodes, both in animals and humans. However, the variety of material and methods used in different experiments means that caution must be exercised when the results of different studies are analyzed and compared. Abdominal electromyograms could help in the clinical evaluation of uterine activity in pregnancy because it is a noninvasive tool that can be easily performed in hospital. It provides complementary information on the muscle, compared with current mechanical obstetric monitoring. There has been no literature review on this subject since that of Wolfs and Van Leeuwen[1] in 1979. There is today a need to establish both controversies and points of agreement on a solid basis. In this article we propose several terms and ideas for standardizing the description and interpretation of uterine electromyograms.

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Uterine structure and activity

Uterine morphologic characteristics and muscle layers. The uterus is a tubular organ whose wall is composed of three coats: an inner mucosa, the endometrium; a surrounding muscle coat, the myometrium; and a thin external serous coat, the serosa. Anatomically the pregnant human uterus can be divided into three parts; the uterine body, the cervix, and the isthmus, which is the junction between the two other parts. During fetal life the uterus develops from the müllerian ducts, which form two tubes whose ends fuse. Depending on the extent of the fusion, the uterus consists of either two horns, as in rats, ewes, goats, and rabbits, or one cavity, as in monkeys and humans. A variety of malformations of the human genitourinary tract can mimic the normal anatomic configurations seen in domestic mammals.[2]

The myometrium consists mainly of two populations of smooth muscle fibers organized in different ways, depending on the species. In animals with a bipartite uterus there is an outer longitudinal layer and an inner circular layer, which cross at a right angle.[3] In the pregnant human myometrium the organization of muscle layers has long been a matter of debate. Current opinion distinguishes (1) an external layer consisting in two sublayers, one (internal) with circular fibers and the other (external) with longitudinal fibers, (2) an intermediate layer that forms the most important part of the myometrium where fibers are diagonally interlaced,

and (3) an internal layer containing circular fibers (Fig. 1).[4-7] At the end of pregnancy, as the uterus increases in size, the external longitudinal layer tends to be localized to the uterine fundus and body, whereas the inner layer may be predominant in the isthmic region.[3] The percentage of muscle fibers at term is 68.8% in the body, 28.8% at the top of the cervix, and only 6.4% at the bottom of the cervix.[7-10] The intricate interlacing of muscle bundles through the various layers in the human pregnant uterus is likely to render its contraction more isotropic than anisotropic during muscle shortening.[11] However, this isotropy may not apply to electromyographic activity because the latter signal is localized in nature and may reflect the anatomic sandwichlike separation of the myometrium into definite layers.

Mechanical activity of the uterus. Contraction of the uterine muscle results in an increase in intrauterine pressure, which is measured with a saline solution–filled, open-tipped catheter or fluid-filled, balloon-tipped catheter positioned in the uterine cavity inside or outside the amniotic bag. Many authors have quantified intrauterine pressure by computing different parameters.[12-21] The interest in measuring the area under the intrauterine pressure curve occurs because the curve is completely independent of the duration of the integration period. However, this measure represents only the overall level of myometrial activity. It is the net contribution of three independent variables, namely the strength, frequency, and duration of contractions.[22] Other parameters can be drawn from analysis of intrauterine pressure curves. Specifically, the values of the maximum rate of rise of pressure with respect to time and of the extrapolated maximum muscle velocity have been proposed for discriminating dysfunctional uterine activity and patterns of labor relating to delivery.[23]

During the first 30 weeks of human pregnancy the uterus exhibits very-low-amplitude contractions, namely, Alvarez waves, at a frequency of one per minute.[12] Then, from the twentieth week, the so-called Braxton Hicks contractions appear. They have higher amplitude and lower frequency (one every 3 to 4 hours). Their action is claimed to be less localized.[24] These contractions become more and more frequent and increase in strength up to the end of pregnancy. At parturition activity is considered to be fully "propagated" to the whole uterus in a short time (about 20 seconds).[1]

Control of myometrial activity. In most species the uterus is thought to be primarily innervated by postganglionic noradrenergic fibers from the sympathetic nervous system.[25] However, there appears to be some species differences; for example, the rat uterus exhibits both adrenergic and cholinergic innervations. Adrenergic fibers predominantly innervate blood vessels,

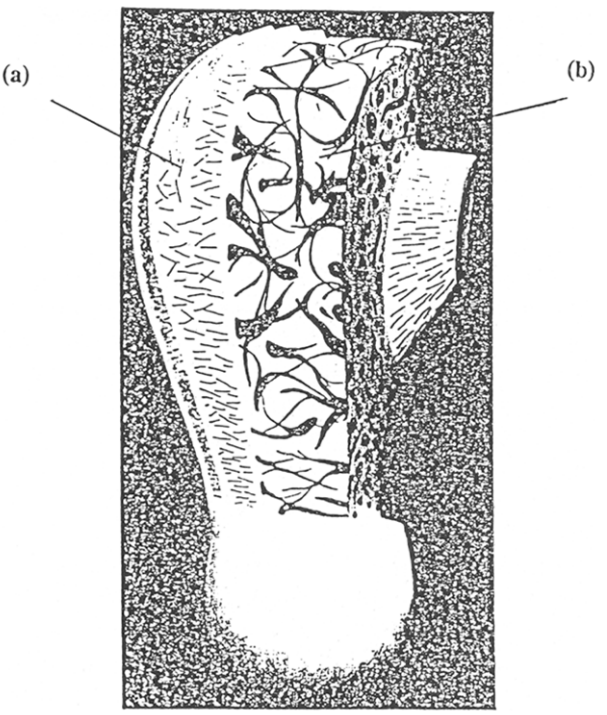

Fig. 1. Structure of human gravid uterus: intermediate most important layer (plexiform layer) consists of diagonally interlaced fibers. On *left side* subserosal layer (external) *(a)* is shown (most external part, longitudinal layer, is hidden); internal circular layer *(b)* is symbolized on *right side* (adapted from Wetzstein[7]).

whereas cholinergic fibers innervate both uterine smooth muscle and blood vessels.[26, 27] A number of other neurotransmitters have been recently described in the female genital tract. They include vasoactive intestinal polypeptide,[28, 29] neuropeptide Y,[30] galanin, calcitonin gene–related peptide,[31] and peptide histidine methionine.[32] Substance P has been hypothesized to convey afferent pathways of the sensory branch of splanchnic nerves, whose resection provokes dysfunctional labor in term rats.[33] However, generally speaking, the extent to which a specialized innervation of the myometrium participates in direct or indirect cellular coupling remains unknown.

Sex steroids also play an important role during pregnancy and parturition. Species differences exist, but common trends can be noted. During pregnancy estradiol concentration reaches a peak in the early morning, whereas plasma progesterone is elevated at night.[34] Estrogens induce uterine hypertrophy; hyperpolarize the cell membrane; and increase action potential amplitude, the length of action potential bursts, and the number of action potentials per burst.[35-41] They also induce the formation of gap junctions.[42] This probably contributes to enhance contractility and conductibility in muscle fibers. Progesterone hyperpolarizes the cell

membrane, but it decreases action potential amplitude and frequency.[39, 40, 43-47] It inhibits the propagation of electrical activity and the formation of gap junctions in several species.[42] Oxytocin induces a quite long, sometimes permanent, depolarization of the cell membrane. It increases action potential frequency, length, and rise time, and decreases the action potential amplitude and propagation velocity.[48-54] It is well known as a powerful uterostimulant. Serum oxytocin levels exhibit a peak during the early hours of darkness in the pregnant rat and rabbit, remain elevated during parturition, and decrease after expulsion of the last fetus.[55-58] Uterine sensitivity to oxytocin increases as pregnancy progresses and reaches a peak shortly before or at parturition.[51, 52, 59, 60] These hormonal changes also correlate with circadian mechanical and electrical activity of the uterus.[61-63] Prostaglandins E and F induce a slow membrane depolarization that initiates or increases the frequency of spike burst discharges. It also increases the resting tonic tension.[48, 64, 65] Initiation of labor is widely believed to correspond to an increase in prostaglandins.[66] No significant circadian time trends could be shown in maternal plasma or amniotic fluid prostaglandins.[67] Various additional influences whose mechanism of action is still obscure are correlated with changes in electrical activity of the uterus. During the last third of pregnancy in the macaque monkey the fetus determines circadian oscillation of myometrial electromyographic activity.[68] There also exists a relationship between myometrial activity and sleep state and breathing in the sheep fetus throughout the last third of gestation.[69] Acute withdrawal of food from the mother has been proved to increase uterine contractility in sheep and monkeys.[70-72] Uterine volume can be an important factor in the regulation of uterine motility. The larger the volume, the more stretched the muscle fibers and the higher the fiber tension that thus modulates the amplitude of contractions.[44]

In summary, the uterus differs between species in terms of shape and the pattern of activity. However, given the basic similarities in structure of the muscle layers and in the evolution of uterine activity during pregnancy, many conclusions drawn from animal analysis can probably be extrapolated to human uterine activity.

Electrical activity

Differences have been shown between electrical activities during pregnancy and parturition. For clarity, it is useful to standardize the main electromyogram parameters. The following terms are used throughout the article: D, Burst duration; Amp, peak-to-peak action potential amplitude; F1, frequency of burst; F2, frequency domain of a whole burst. Describing electromyograms, many authors have also made a distinction between two types of wave: a slow wave (Fig. 2, b), with a period equal to the contraction duration, and a fast wave (Fig. 2, c) superimposed on the slow wave. Recently, authors have separated this fast wave into a low-frequency band (FW_L) and a high-frequency band (FW_H). Furthermore, many authors have studied electrical activity propagation in terms of pacemaker areas, synchronization (time relationship between mechanical and electrical activities), and propagation velocity (or time delay), referred to as group propagation when calculations are based on electromyogram envelopes and classic propagation when calculations are based on electromyogram signals.

Electrical activity at the cell and tissue levels. The uterine electromyogram is the result of electrical activity generated at the microscopic level. The most common techniques used to measure electrical potentials at the cellular level are the glass microelectrode (with a diameter < 1 μm, usually filled with a 3 mol/L potassium chloride solution) and the "gap" techniques, such as the sucrose-gap method. Because uterine muscle cells are small, rich in collagen, and contract quite vigorously, microelectrodes have to be appropriately modified. The sucrose-gap method is the most frequently used method to record uterine cellular activity. Electrical activity is the trigger of muscle fiber contraction. The resultant mechanical effect depends on two parameters involved in the contractile process, namely, excitation and propagation of electrical activity.

Excitation. Electrical activity at the cellular level can be described by means of two types of potential, the resting potential and the action potential.

RESTING POTENTIAL. The resting potential is the difference between the negative inside and the positive outside potential of a resting cell membrane. It is directly related to the concentrations of calcium, potassium, and chloride ions. When their concentrations change, the cell membrane becomes hyperpolarized (resting potential more negative) or depolarized (resting potential more positive). For uterine smooth muscle cells it is difficult to give resting potential absolute values because it fluctuates slowly in a sinusoidal manner. In domestic animals it ranges from -55 to -65 mV during pregnancy.[35, 36, 40, 46, 53, 73-76] In pregnant women uterine resting potential usually ranges from -65 to -80 mV.[77]

ACTION POTENTIAL. The action potential is related to abrupt variations of cell permeability to K^+, Na^+, and Cl^- ions and corresponds to a decrease in the positivity of the outside cell surface. When the resting potential reaches a threshold, action potentials are generated. Depending on both species and techniques used to measure action potentials, authors have reported various values. In small mammals it ranges from 33 to 68 mV during pregnancy.[35, 45] In women Kuriyama and

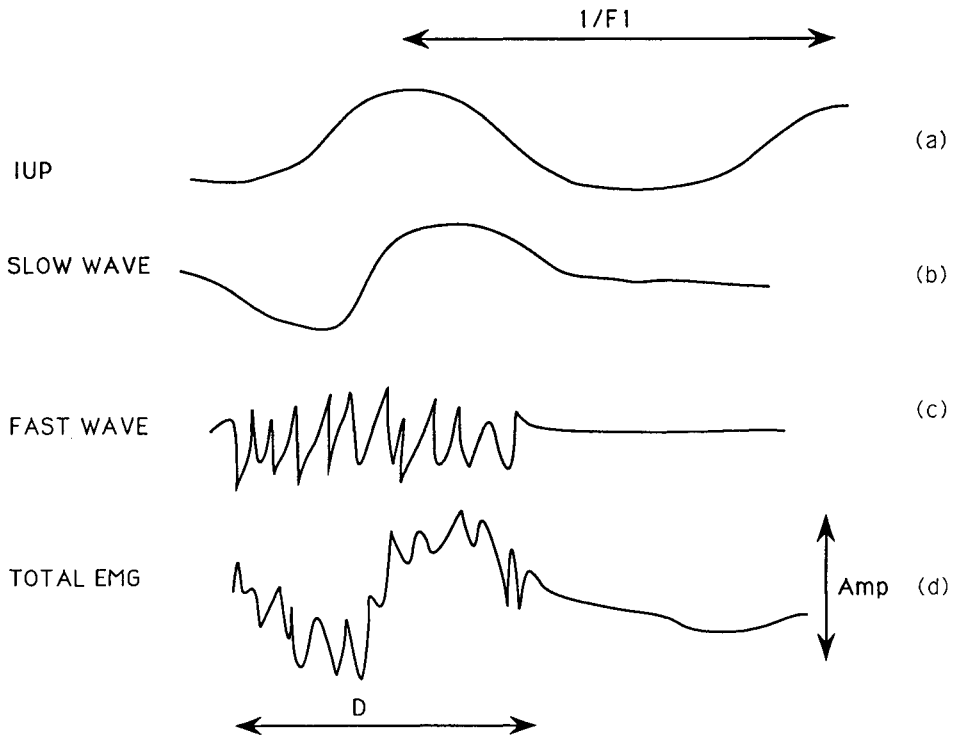

Fig. 2. Theoretic description of uterine electromyogram *(EMG). IUP,* Intrauterine pressure.

Csapo[45] report values of 12 to 25 mV. Action potentials usually occur in bursts that can be characterized by two types of frequency. F1 (<0.1 Hz) represents burst occurrence and reflects the excitability state of the cells. F2 (1 to 10 Hz) is the intrinsic spike frequency within each burst and is related to the intensity of the mechanical contraction.[53]

EXCITATION-CONTRACTION COUPLING. Like striated muscle, uterine smooth muscle cells contain thin actin and thick myosin filaments. The contractile mechanism of myometrial cells involves the interaction of these two specific protein filaments. The relationship between electrical excitation (i.e., appearance of action potentials) and the mechanical effect resulting from actin and myosin interaction is called the excitation-contraction coupling. This coupling is mediated by calcium ion fluxes. The intracellular Ca^{++} is very low when muscle is at rest. The appearance of action potentials is associated with an increase in the intracellular Ca^{++}, which in turn, controls the interaction between the contractile proteins.[1, 78]

Propagation

PACEMAKERS. Like cardiac cells, myometrial cells can either be excited by action potentials generated from a neighboring cell (pacefollower cells) or generate their own impulses (pacemaker cells). In pacefollower cells spikes arise abruptly out of the resting potential, whereas in pacemaker cells spikes are preceded by a slow depolarization called a prepotential.[44, 53, 79] However, myometrial cells differ from cardiac cells in that each cell can be alternately pacemaker or pacefollower. Furthermore, there is no evidence for a fixed anatomic pacemaker area on the uterine muscle. An action potential burst can originate from any uterine cell, and the pacemaker cell(s) can change from one contraction to another.

GAP JUNCTIONS. Gap junctions are intercellular channels that directly link cells to their neighbors, allowing passage of inorganic ions and small molecules. They appear in areas of close apposition between cells as zones of paired parallel membranes, of unusually smooth outline, separated by a narrow space of constant width: the gap.[80] Gap junctions have been shown to appear at delivery in various species. In women successful progress of labor is related to an increase in gap junction area. However, labor may not progress, although gap junctions are present and the uterus contracts, because of some other mechanism malfunction.[81] Gap junctions have been shown to increase in the same proportions in the two distinct muscle layers in rats.[82] Sims et al.[83] demonstrated that the length constant of the electrotonic spread of currents in the longitudinal myometrium of rats increased significantly at delivery, with a 33% decrease in cytoplasmic resistance and a 46% increase in membrane resistance. Gap junctions are thus thought to be responsible for improving elec-

Table I. Characteristic electromyogram parameters during pregnancy

Year	Authors	Species	Electrode location	Term	D (min)	FI (burst/hr)	Slow wave F (Hz)	Slow wave Amp (mV)	Fast wave F2 (Hz)	Fast wave Amp (mV)
1989	Legrand et al.[96]	Rats	Horn	First trimester	0.25	40				0.064
1984	Demianczuk et al.[84]	Rabbits	Horn	Pregnancy	5	1-6				0.2-0.4
1985	Taverne and Scheerboom[66]	Goats	Horn	Third trimester	6.2-8.3	0.7-1.1				
1989	Van Der Weyden et al.[98]	Dogs	Horn	Third trimester	3-10	2-5				
1981	Van Der Weyden et al.[97]	Ewes	Horn	Midterm	6.1-7	1.3-1.8				<0.15
1981	Van Der Weyden et al.[97]	Ewes	Horn	Term	7.5-9.2	0.5-0.9				<0.46
1982	Harding et al.[94]	Ewes	Internal	Second half	6	1				
1983	Toutain et al.[99]	Ewes	Cervix	Third trimester	7	1.2				0.2-0.6
1983	Toutain et al.[99]	Ewes	Horn	Third trimester	8.2					0.4-0.6
1984	Sigger et al.[100]	Ewes	Internal	Third trimester	4-10	1.4				
1984	Sigger et al.[100]	Ewes	Isolated tissue	Third trimester	4.5	3.5				
1984	Garcia-Villar et al.[101]	Ewes	Horn	Second trimester		2.45				
1984	Garcia-Villar et al.[101]	Ewes	Cervix	Third trimester	6.8					
1984	Garcia-Villar et al.[101]	Ewes	Horn	Third trimester	8.3	0.96				
1987	Haluska et al.[102]	Mare pony	Internal	Second half	>2	3				
1982	Germain et al.[93]	Monkeys	Internal	Third trimester		6			~1	0.1-0.3
1992	Mansour et al.[103-105]	Monkeys	Internal	Third trimester					0.02-4.7	
1986	Marque et al.[106, 107]	Humans	External	Third trimester	74				0.2-3	
1992	Gondry et al. (unpublished observations)	Humans	External	Midterm	30-100				0.2-1.2	

Internal, On corpus uteri; external, on abdominal wall.

trical coupling between myometrial cells. They are believed to allow synchronization and coordination of contractile events of different myometrial regions and hence to help fetal expulsion.[80, 84, 85]

Summation. Uterine smooth muscle cells exhibit negative resting potentials with small and slow spontaneous fluctuations. When resting potential fluctuations reach a threshold, isolated or bursts of action potentials are induced with peak-to-peak action potential amplitude (Amp) ranging from 33 to 68 mV, burst frequency (F1) <0.1 Hz, and action potential frequency within burst (F2) ranging from 1 to 10 Hz. F2 appears to control the intensity of mechanical contractions. In most species myometrial cells can either be pacemakers or pacefollowers with no evidence for a fixed pacemaker area. Gap junctions have been shown to appear at parturition and to improve the electrical coupling between uterine cells.

Whole-organ electromyogram recordings: Myometrial level. For clarity, the term "myometrial" will be used throughout the paper to represent internal recordings of electromyograms with electrodes located on the uterus, as opposed to "abdominal" recordings, where electrodes are located on the abdomen.

For obvious ethical reasons most of the myometrial electromyogram recordings have been performed on animals. Nevertheless, a few experiments were performed in the 1950s on women undergoing cesarean section,[86, 87] and nowadays some authors have recorded human myometrial electromyograms by carefully positioning endouterine electrodes in close apposition to or in the uterus body.[1, 88, 89] Cervical electromyograms were recorded either with wire or surface electrodes.[90-92]

Bipolar insulated stainless steel wire electrodes[72, 82, 93-97] or silver–silver chloride bipolar electrodes[57, 87] were used for these experiments. They were directly positioned on or in the uterine wall either during pregnancy or during parturition.

Uterine electromyograms during pregnancy. Table I summarizes D, Amp, F1, and F2 averaged values noted by authors who have studied pregnancy activity.

D, Amp, F1, and F2. Legrand et al.[96] recorded some electromyographic activity from the first day of rat pregnancy, but in ewes other authors did not detect any activity at the beginning of pregnancy, either on the corpus[100, 101] or on the cervix. Thereafter the uterus was found to be active only 11% of total pregnancy time.[101] In goats no statistical difference in D and F1

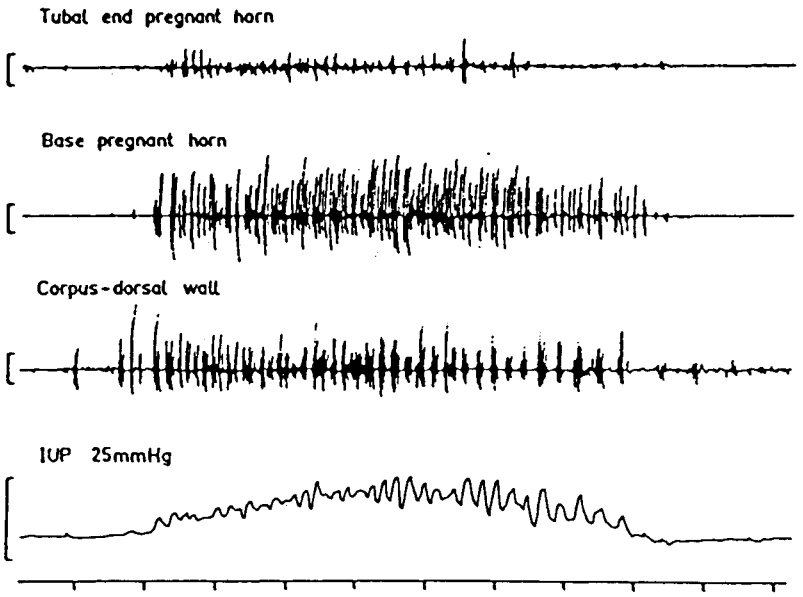

Fig. 3. Relationship between uterine electromyogram activity at three sites and intrauterine pressure *(IUP)* at 124 days of gestation in ewes. Electromyogram calibration *bar,* 1 mv. Intrauterine pressure calibration *bar,* 25 mm Hg. Time in minutes. (From Harding et al.[94])

values was found between the two horns.[66] Many authors[66, 72, 96, 102, 108] have observed that D is rather variable during gestation in various species, leading to the definition, in ewes, of contractures (D >3 minutes) specific to gestation and contractions (D <3 minutes)[72, 94, 108] related to labor and found in only 14% of electromyographic pregnancy activity.[108] Hsu et al.[72] showed that the contracture power spectrum has 65% of its frequency content below 0.11 cycles/min and that contraction power spectra have 96% of their frequency content above 0.11 cycles/min. These frequencies correspond to the F1 frequency domain. Food withdrawal and darkness induce a shift of the electromyogram power spectrum content toward the high frequencies. F1 was found to decrease by the end of pregnancy in the mare pony.[102] In monkeys F1 and F2 values were also found to vary depending on individuals and on recording time; they were higher at 8 PM than at noon.[93] Some authors did not find any electrical change during the last month of pregnancy.[99] Germain et al.[93] noticed that F2 varied within each burst and came to the conclusion that there was a complex relationship between F2 and contraction intensity. Using power spectral densities Mansour et al.[103-105] noted two typical frequency activities within the fast-wave range: a low-frequency band (FW_L) (<1.2 Hz) and a high-frequency band (FW_H) (centered around 3 Hz).

SYNCHRONIZATION OF ELECTRICAL VERSUS MECHANICAL ACTIVITIES. Many authors observed that mechanical activities were almost always associated with electrical signals (Fig. 3).[72, 93, 95, 103-105] Working on electromyogram envelopes averaged over 8-second periods, Hsu et al.[72] demonstrated that electromyogram envelopes and intrauterine pressure had similar power spectra. Mansour et al.[103-105] stated that FW_L originated earlier than intrauterine pressure onset, whereas FW_H was restricted to the rising edge of the intrauterine pressure curve.[105]

PROPAGATION. Sigger et al.[100] found no valid statistical concordance between two electrical activities measured in the uterus and in the distal part of one uterine horn completely separated from the rest of the uterus. During their experiments on rhesus monkeys Hsu et al.[72] observed nonpropagated local electromyogram activities that were not associated with a corresponding rise in intrauterine pressure.[72] Some authors observed that electrical activity was more frequent in the uterine body than in the horn.[95] Van der Weyden et al.[97] noted episodes of myometrial electrical activity mainly located on horn extremities and composed of single spikes or short bursts (5 to 15 seconds). Otherwise, many authors found that electrical activities were usually well synchronized,[93, 94] including activities arising from horns and cervix.[99] Krishnamurti et al.[95] assumed that long irregular trains (D >120 seconds) during gestation represented activity of isolated groups of myometrial cells. They considered the myometrium a multiple unit during this period. In rats during early pregnancy Legrand et al.[96] observed action potential bursts with uterotubal-cervix group propagation velocity ranging from 0.3 to 0.6 cm/sec. From day 3 to day 5 group propagation and synchronization disappeared. In ewes Toutain et al.[99] observed that regular spiking activity of the gravid horn and cervix were nearly always synchronous. Group propagation analysis of these activities sometimes showed a short delay (30 to 90 seconds) with no evidence for a fixed pacemaker area. In monkeys Mansour

Table II. Characteristic electromyogram parameters at delivery

Year	Authors	Species	Electrode location	Term	D (sec)	FI (burst/min)	Slow wave F (Hz)	Slow wave Amp (mV)	Fast wave F2 (Hz)	Fast wave Amp (mV)
1984	Demianczuk et al.[84]	Rabbits	Internal	Parturition	30	1				
1982	Germain et al.[93]	Monkeys	Internal	Parturition					~2-4	~0.06
1946	Dill and Maiden[86]	Humans	Internal/external	Parturition			*	*	*	*
1950	Steer and Hertsch[109]	Humans	External	Parturition			*	1-5	0.3-2	0.1-0.5
1952	Levy-Solal et al.[110]	Humans	External	Parturition	<40				0.25-1	1-3
1954	Steer[111]	Humans	External	Parturition					0.2-2	0.05-0.5
1958	Larks et al.[112, 113]	Humans	External	Parturition			0.005	5-10		
1958	Hon et al.[87]	Humans	External	Parturition			*	<5	0.5-2	0.1-0.3
1958	Hon et al.[87]	Humans	Internal	Parturition			*	0.5	*	*
1970	Wolfs et al.[88]	Humans	Intrauterine	Parturition	40-60				0.6	1
1970	Wolfs et al.[88]	Humans	External	Parturition	40-60				*	0.05-0.2
1979	Wolfs et al.[1]	Humans	Internal	Parturition	40	0.4			0.2-0.7	0.4-1
1984	Lopes et al.[89]	Humans	Internal	Parturition					*	0.1-1.8
1984	Planes et al.[114]	Humans	External	Parturition	60		<0.03	1-15	0.03-1	0.02-0.5
1986	Marque et al.[106, 107]	Humans	External	Parturition	55		*	*	0.2-3	
1991	Pajntar et al.[90-92]	Humans	Cervix	Parturition					0.34	0.1-0.5

Internal, On corpus uteri; external, on abdominal wall.
*Observed but no available numeric data.

et al.[103] attempted to identify the existence of classical propagation by computing the delay between two internal signals measured with two unipolar electrodes 2.5 mm apart. With cross-correlation techniques they could not demonstrate any statistically valid delay. With the coherence function they obtained very low values, reflecting the complexity and nonlinearity of the propagation process.

Uterine electromyogram during parturition

D, AMP, F1, AND F2. Their averaged values are listed in Table II. Whatever the species, most authors observed a dramatic change in myometrial activity, either 4,[93] 24,[66, 84, 94, 97, 100] or 72 hours[95, 99] before parturition. First, a clear inhibition of all myometrial activity occurred,[66, 99] then F1 was usually observed to increase[94, 98] and D to decrease,[66, 94, 97] except for Wolfs and Van Leeuwen,[1] who observed an increase in D throughout labor. Amp was reported to increase.[1, 97] Nevertheless, potentials recorded by Lopes et al.[89] in women exhibited a wide range of amplitudes. Pajntar et al.[90, 91] compared human cervical electromyograms recorded with a lead in the longitudinal and circular layers. They hypothesized that in the cervix longitudinal muscle fibers were active during contractions and contributed to cervical dilatation, whereas circular muscle fibers were active between contractions, increasing resistance to cervical dilatation.[92] Toutain et al.[99] pointed out that irregular spiking activity increased between episodes of regular spiking activity in ewes, leading to almost continuous activity during the expulsion of the conceptus, whereas Wolfs and Rottinghuis[88] stated that there was no more electrical activity between contractions in women as soon as labor started.

SYNCHRONIZATION OF ELECTRICAL VERSUS MECHANICAL ACTIVITIES. A good correlation between electrical and mechanical activities was usually noted as soon as labor was well established.[1, 89] Hon and Davis[87] tested a woman undergoing a cesarean section. They found that what they called AC potentials (fast wave) started before the intrauterine pressure rising edge, and that DC potentials (slow wave) were in phase with intrauterine pressure. Fast waves were usually detected before the intrauterine pressure increase[87-91] and were restricted to the rising phase of intrauterine pressure.[1, 90, 91, 103-105] Lopes et al.[89] concluded that improvement of uterine coordination, in terms of synchronization, is not responsible for the increase in uterine contractile strength during human labor, because it is already well established at the beginning of labor.

PROPAGATION. Electromyographic activity during labor is usually described as regular, well-defined electromyogram bursts,[84, 98] assumed to correspond to the rhythmic synchronous activity of different cells.[95] Taverne and Scheerboom[66] noted in ewes that episodes of myometrial electrical activity were synchronous in both horns. Krishnamurti et al.[95] considered the myometrium to be a single unit at parturition. Sigger et al.[100] observed the same electrical evolution both in a ewe uterus and in the distal portion of one uterine horn separated from it, where absence of adrenergic nervous innervation was shown histologically. Furthermore, 90% of the observed bursts occurred in phase in the uterus and in the distal part still connected to the rest of the horn, through the oviduct and the ovarian blood vessels with adrenergic axons present along them. They concluded that separated uterine muscle in vivo has rhyth-

micity resembling that of intact myometrium and that systemic or local circulating factors were not responsible for synchronizing uterine activity before parturition. Nevertheless, these factors do play a major role in the increase in uterine activity.[100] Many authors consider that there is no specific localized pacemaker area in the uterus and that each myometrial cell could be a possible pacemaker.[1, 86, 88, 89, 94, 98] Indeed, during dog labor propagated electromyogram bursts (using group propagation notion) can first appear at any electrode implantation site.[98] Krishnamurti et al.[95] postulated the existence of pacemaker areas localized in horns and raised the possibility of group tubocervical propagation in ewes. In the macaque monkey Duchêne et al.[115] showed that differences in times of onset of burst activities (in terms of group propagation) derived from different electrode leads remained constant during the whole of parturition. Thus they concluded that some pacemaker area could remain active during the whole of labor, but they did not suggest any localization. On another hand, they attempted to demonstrate linear propagation between two close bipolar leads. None of the classic techniques, such as the correlation function, the cepstrum, or the deconvolution methods permitted them to conclude on a classic propagation of elementary potentials. Wolfs and Van Leeuwen[1] considered that characteristic changes in electrical and mechanical activities during labor were based to a large extent on the gradual facilitation of electrical conduction. They estimated group propagation velocity of electrical activation to be >2 cm/sec.[1]

Summation. In animals, whatever the species, most authors measure myometrial electromyogram Amp ranging from 64 to 600 μV during pregnancy without making any distinction between slow and fast waves.[84, 93, 96, 97, 99] Indeed, only the fast wave is obtained at the myometrial level. These pregnancy Amp values are thus related to the fast wave. During pregnancy, D, F1, and F2 values differ considerably from one species to another, probably because of the difference in morphologic characteristics and size. Roughly, electromyogram bursts last from D = 3 to 10 minutes with F1 ranging from 0.5 to 6 contractions per hour. For the fast-wave range in monkeys Mansour et al.[103-105] define two specific frequency bands: FW_L (< 1.2 Hz) and FW_H (around 3 Hz).

Most authors agree that at parturition, after a period of inhibition of electrical activity lasting a few hours, F1 strongly increases up to about 1 contraction per minute, D decreases to values ranging from 30 to 75 seconds, and F2 increases twofold to fourfold. In women during labor Amp ranges from 0.1 to 1.8 mV.[1, 88-92] F1 and F2 increase and D decreases 24 to 48 hours before parturition.

Most authors agree on the synchronization between electrical and mechanical activities, noting that bursts are mostly restricted to the rising phase of intrauterine pressure.[1, 103] Only Mansour et al.[104] state that the FW_L starts before the intrauterine pressure increase and that the FW_H is restricted to the rising edge of the intrauterine pressure curve. Group propagation is usually noted during pregnancy. It is more evident at parturition; a velocity of 2 cm/sec has been reported.[1] No classic propagation has been demonstrated to date.

Whole-organ electromyogram recordings: Abdominal level. The term *abdominal* is used throughout the article to represent external recordings of electromyogram with electrodes located on the abdomen. The signal obtained has been defined by Steer and Hertsch[109] as the electrohysterogram.

Only one author has compared the myometrial electromyogram and abdominal electrohysterogram in an animal (cynomolgus monkeys).[103-105] All other experiments have been performed on women. In all cases silver–silver chloride bipolar electrodes were used with electrode interspace ranging either from 10 to 20 cm[87, 110, 112, 113] or from 2.5 to 5 cm.[88, 103-107, 109, 111] Electrodes were usually positioned above the uterus along a vertical median axis[106, 107, 114] or transversally on the right and left parts of the fundus.[87, 88, 109-113]

Uterine electrohysterogram during pregnancy

D, Amp, F1, and F2. In humans electrohysterogram activity can be detected as early as the eighteenth week of pregnancy, and no influence of placental insertion on electrical activity could be shown.[116, 117] Skrablin et al.[117] found that 95.7% of women with symptoms of preterm labor had term delivery if no electrical activity was present. If electrical activity was present, preterm labor would occur in spite of tocolytic treatment in 20% to 50% of the cases. By means of internal unipolar and abdominal bipolar electrodes, Mansour et al.[103-105] demonstrated the relationship between internal and abdominal electromyograms, in monkeys. They found that internal electromyogram amplitude was larger than abdominal electrohysterogram amplitude. Abdominal and myometrial electromyogram fast-wave spectra exhibited the two basic activities (FW_L: around 1.2 Hz; FW_H: around 3.5 Hz) but with different relative powers. By means of cross-correlation techniques on signal envelopes filtered between 2 and 4 Hz they showed that internal and abdominal activities were synchronous ($r = 0.75$). They concluded that abdominal electrohysterogram was probably derived from uterine activity. Nevertheless, a moving average modeling method showed that there was no linear relationship between myometrial and abdominal electromyogram activities.[103] Marque et al.[106, 107] demonstrated the same activities of the fast wave (FW_L: 0.2 to 0.45 Hz; FW_H: 0.8 to 3 Hz) on human abdominal recordings. With discriminant analysis these authors computed a criterion

representative of contraction efficiency on the basis of spectral and temporal parameters of the fast wave alone. Inefficient gestational contractions exhibited F2 mainly in the low-frequency band.[106, 107]

SYNCHRONIZATION OF ELECTRICAL VERSUS MECHANICAL ACTIVITIES. Gondry et al.[116] showed that in pregnant women 89% of contractions recorded by means of abdominal electrohysterogram were temporally related to mechanical activity.

Uterine electrohysterogram during parturition. Most studies of abdominal electrohysterogram were performed on women for clinical evaluation. The electrohysterogram was described in terms of amplitude or frequency (Table II).

D, AMP, F1, AND F2. Fast waves were observed by most authors. In only a few cases, a slow wave was noted,[86, 87, 109, 112, 113] whose period was equal to the duration of the related contraction.[114] Dill and Maiden[86] were the first to observe what they called a DC signal: definite deflections obtained with abdominal electrodes under caudal anesthesia, when striated muscle effects must be at a minimum. They stated that slow-wave Amp was related to contraction intensity. Larks et al.[112, 113] analyzed the human electrohysterogram filtered between DC and 1 Hz and characterized the signal by its shape. The slow waves they observed were biphasic, starting with a negative deflection. Hon and Davis[87] performed one experiment on a woman undergoing cesarean section and considered only the slow-wave component of the electrohysterogram. Because this slow wave could be reproduced on a male abdomen by stretching the skin, they came to the conclusion that skin stretching was entirely responsible for all types of abdominal activity. However, most authors consider the electrohysterogram fast wave to reflect uterine contractions.[88, 106, 107, 109-111, 114, 116-118] Sureau[119] based his study on fast-wave (F >0.22 Hz) amplitude and found that normal labor was mostly associated with Amp >400 μV. On the contrary, Steer[111] claimed that amplitude had no clinical meaning. A good synchronization between myometrial electromyogram and abdominal electrohysterogram was usually observed,[88] although abdominal electrohysterogram amplitudes were lower than electromyograms obtained with sutured myometrial electrodes.[88, 109] In some cases no activity was seen in the lower portion of the uterus.[109] By means of a pattern recognition technique applied to the uterine electrohysterogram fast wave, Val et al.[118] identified the 0.2 to 0.5 Hz band as being the most relevant frequency band for contraction versus rest classification. Marque et al.[106, 107] showed that the human parturition electrohysterogram exhibited a relative sliding of the FW_L toward higher frequencies and an increase in the relative power of the FW_H compared with pregnancy activity.

SYNCHRONIZATION OF ELECTRICAL VERSUS MECHANICAL ACTIVITIES. Many authors concluded that synchronization between mechanical activity and electrical abdominal fast waves was good.[86-88, 103-107, 109, 111, 114, 116] In some cases mechanical activity could be observed, although there was no abdominal electrical activity.[110, 111, 119] Sureau[119] explained this by the fact that electromyographic activity was not always present everywhere at the same time and that electrodes only pick up electrical activity from a restricted area. Thus absence of activity only has a local meaning. Consequently, he proposed that no cesarean section should be performed if diagnosis was only based on abdominal electrical recording. In his opinion, abdominal electrical modification implies clinical modification but not the reverse.[119] Steer[111] claimed that absence of electrical activity implies uterine inertia but not vice versa.

PROPAGATION. Steer and Hertsch[109] observed that there was group propagation of electrical activity at the beginning of labor. Activity either started at the same time at several points or was propagated very quickly at the beginning of labor. Because they observed different shapes for the left and right uterine horns, Larks et al.[113] concluded on the presence of a pacemaker in the right horn, with a group propagation velocity of 2 cm/sec. Planes et al.[114] claimed that there is a fixed pacemaker area for the specific slow wave in each woman. Levy-Solal et al.[110] observed low-frequency waves and identified three groups of electrical activities. Group A (F2 = 0.25 to 1 Hz) corresponded to fast cervical opening and was assumed to be associated with electrical intercellular coordination controlled by a single focus. Group B had a flat recording, and group C had electrical hyperactivity associated with slow cervical opening and asynchronism and hypertony of the uterus.

Summation. In women some uterine electrohysterogram activity can be recorded from the eighteenth week of pregnancy.[116] Two types of electromyographic activity for abdominal recordings are observed: a slow-wave or so-called DC potential[87] on which the usual fast waves are superimposed.[79, 87, 88, 106, 107, 109-111, 114] This slow wave is synchronous with the intrauterine pressure[114] and is usually biphasic; its frequency content thus ranges from 0.014 to 0.033 Hz and its amplitude ranges from 0.5 to 15 mV.[87, 111-113] Fast waves exhibit Amp values ranging from 0.02 to 0.5 mV.[87, 88, 109, 111, 114] Abdominal electrohysterogram Amps are lower than at the myometrial level.[88] Mansour et al.[103-105] have demonstrated in the monkey that abdominal electrohysterogram spectra exhibit the same two basic activities of the fast wave as do myometrial electromyogram spectra but with different relative powers. Marque et al.[106, 107] also define two main components of the human elec-

trohysterogram spectral fast wave: a low-band FW_L (0.2 to 0.45 Hz) always present during both pregnancy and parturition contractions and a high-band FW_H (0.8 to 3 Hz) only noted during efficient parturition contractions. Most authors conclude that synchronization between mechanical activity and the electrohysterogram fast wave is good.[86-88, 103-107, 109, 114, 116] Group propagation is reported to be well established during labor, leading to a propagation velocity of about 2 cm/sec.[1]

How should uterine electromyograms be recorded and interpreted?

Recording electrodes and signal analysis methods. Electromyogram and electrohysterogram recordings and analysis have been performed quite extensively since the 1950s, but materials used in these experiments and methods applied for signal analysis have been numerous. This variety need not have deleterious consequences on the validity of the result, provided a minimum of precautions are taken in their interpretation. Basically, all types of recording contain the same information. Myometrial electromyograms collected by surface electrodes represent the summation of cellular activities. This spatial integration implies an increase in signal amplitude and is usually associated with a low-pass filtering effect that has been extensively investigated and modeled in striated muscles.[120, 121] The electromyogram of the latter muscles are, however, of a much higher frequency band than is the uterine muscle electromyogram, and the models used (i.e., propagation of action potentials along a linear fiber with constant velocity) are inadequate for uterine muscle description. Direct quantification of this integration effect concerning the uterine electromyogram is not possible from works performed in striated muscle. Nevertheless, it is currently admitted that the power spectral density of randomly summated signals essentially reflects the properties of the individual components.[121, 122] This leads to the conclusion that the power spectral density of the whole muscle signal reflects the spectral properties of individual cells.[121] Abdominal electrohysterograms exhibit the same activities as internal electromyograms, except that they are low-pass filtered by the conductive properties of tissues lying between the uterus and the electrodes. This attenuation of high frequencies, usually noted for frequencies >100 Hz, has been shown to depend on the distance between the muscle and the recording site, on the conductive properties of the tissues underlying the electrodes, and also on the skin impedance.[121, 123] The latter (skin impedance) can be considerably reduced by a careful preparation of the skin (rubbing and cleansing with ether and acetone).

It is important to place electrodes properly. Quantitative interpretation of results can be rendered difficult by the perturbation induced with a reference electrode located too close to the active electrodes.[90-92, 114] A low input impedance electrode whose potential is set at zero (such as a reference electrode) modifies the electrical fields and hence the signals recorded by the active electrodes if it is positioned close to them.[124] Because there is no specific fixed pacemaker area, myometrial recording electrodes can be positioned anywhere on the uterus, provided there are sufficient muscle fibers. Because the cervix is largely a connective organ (its muscle fiber content is only 6.5%), special attention should be paid to the clinical interpretation of cervical electromyogram recordings.[90-92, 99, 101] Indeed, cervical signals are probably more affected by noise artefacts because of tissue stretching during cervical dilatation, which greatly modifies fiber distribution and interelectrode distance. Abdominal electrodes can be located anywhere so long as they are above the corpus uteri. However, placement along the vertical median axis provides a better signal/noise ratio because of a closer contact and a more constant position of the uterus relative to the abdominal wall during contractions.

For electrode configuration, most authors choose to record both myometrial and abdominal electromyograms with bipolar electrodes. So far only Mansour et al.[103-105] have obtained noiseless myometrial electromyograms with monopolar electrodes. However, for abdominal recordings it is imperative to use bipolar electrodes, because the signal/noise ratio is less than for internal ones. Bipolar electrodes reflect the difference between the two signals present below the two electrodes. Common noise, such as maternal electrocardiogram, maternal movements, electrode movements, and power line interference are thus efficiently rejected. An efficient common mode rejection is expected when the electrode interspace is small. When authors have positioned bipolar abdominal electrodes far away from each other (10 to 20 cm),[87, 98, 99, 101-105, 108-110, 112, 113, 115] electrode interspace was probably too large for efficient common mode rejection. The bipolar recording mode affects the electrohysterogram spectral content. With the usual model of action potential propagating with a constant speed along a striated muscle fiber, power spectral density of electromyograms has been shown to depend on interelectrode distance, on the propagation velocity, and on the frequency band of the action potential.[121] Bipolar recording induces a high-pass filtering effect, thus eliminating the very low frequencies; there is also an increase in the higher frequencies when the distance between electrodes is small compared with the distance between the fiber and the recording electrode pair.[120, 121, 123, 125] For abdominal electrohysterogram bipolar recording the interelectrodes distance is

usually large enough to avoid the enhancement of high frequencies. The main expected effect of this recording mode is a high-pass filter eliminating the low frequencies. The cutoff frequency cannot, however, be extrapolated from the work done on striated muscles, because the model is inadequate.

As a consequence, the monitoring of human uterine activity should only be performed with bipolar abdominal electrodes, even though the bipolar recording mode induces a high-pass filtering of the signals. Abdominal electrohysterograms contain "almost" the same information as myometrial electromyograms except that they are low-pass filtered because of tissue filtering. Otherwise, a complete temporal and spectral electromyogram characterization requires monopolar myometrial electromyogram recordings.

It is currently recognized that the uterine electromyogram frequency content ranges from 0 to <5 Hz, whatever the species. There are minor variations depending on species, because the smaller the uterus the higher the electromyogram frequency content. Digital analysis of the signals with a sampling frequency close to 10 Hz is appropriate in all cases and has to be associated with an antialiasing filter adjusted to a cutoff frequency of 5 Hz.[126] A high-pass filter is also often necessary to eliminate baseline fluctuations. However, the cutoff frequency needs to be carefully chosen. The very low frequencies, as discussed subsequently, can reflect either mechanical artifacts or genuine electrical activity. The choice of the cutoff frequency will thus depend on the frequency bands to be analyzed.

A few authors have worked on signals that were averaged over 8- to 32-second windows, which means that they have studied the periodic characteristics of the signal (F1) but did not attempt to get information on the content of each burst.[72, 94, 108] Although this averaging technique allows comparison of the occurrence of intrauterine pressure waves and electromyogram bursts, it leads to a strong low-pass filtering of the signals. Consequently, signals can be averaged only if investigation of all their frequency components is not required.

Temporal signal. Many authors have characterized the abdominal or myometrial electromyogram signals by means of Amp (summarized in Tables I and II). Although Amp value has a limited significance, it increases relative to noise as pregnancy progresses. This may reflect an increasing number of simultaneously active cells, either because of tissue growth or enhanced synchronization of firing cells. It is very important to clarify several points concerning signal amplitude. As Pajntar and Rudel[92] remarked, electromyogram amplitude is heavily influenced by various factors, such as electrode type and geometry, recording electrode arrangement, the distance between them, electrode distance with respect to the recorded muscle fibers, differences in impedance of the tissue-electrode contact for external recordings (which in turn depends on pressure of the electrodes and on the chemical properties of the interface electrolyte/metal),[123] fiber distribution, etc. Furthermore, the amplitude of signals derived from abdominal recordings is influenced by skin filtering, which differs from one woman to another. In agreement with these phenomena, Lopes et al.[89] observed a large intersubject range of electromyogram amplitudes from 100 μV to 1.8 mV. Therefore signal amplitude cannot be considered as an absolute reference, and it is clearly impossible to compare amplitudes obtained from different experiments, especially under external recording conditions. Comparisons between electromyograms recorded on the same patient at different times can be performed if there is no change in the experimental setup and if the electrodes have not been moved. Only in this context can electromyogram amplitude trends be observed and analyzed. Otherwise, as Steer already announced as early as 1954, it is inadequate to characterize and classify electromyograms only on amplitude parameters.[90-92, 95]

For external abdominal electromyogram recordings two opposite standpoints have been adopted. Some authors denied that abdominal recordings could be representative of uterine activity. However, they have only studied the electrohysterogram in a frequency band corresponding to the slow wave.[86, 87, 112, 113] This slow wave is only observed with abdominal recordings, where fast waves are superimposed on them. It is really doubtful whether the slow wave has any physiologic meaning because no equivalent activity in this frequency band is noted, either at the cellular or myometrial level. Even if it had an electromyogram origin, it would never be possible to distinguish it from mechanical artifacts such as skin stretching or electrode movements because these two types of activity cover the same frequency band. Consequently, all very-low-frequency components of a uterine electromyogram (<0.03 Hz) are meaningless. On the contrary, the study of the electrohysterogram in a frequency band corresponding to the fast wave has convinced most authors that the abdominal electrohysterogram is representative of uterine activity. Moreover, they observed synchronous myometrial and abdominal electromyogram activities,[1, 72, 86, 88, 89, 92, 99, 102, 108, 109] which were also temporally correlated with mechanical activity.[106, 107, 114, 116] From these observations it can be concluded that abdominal activity is representative of genuine uterine electromyogram activity only when it is observed in the frequency band corresponding to the fast wave.

Clearly, both electromyograms and electrohysterograms are temporally correlated with mechanical activity during pregnancy and parturition, whatever the species. A good correlation between the electromyogram

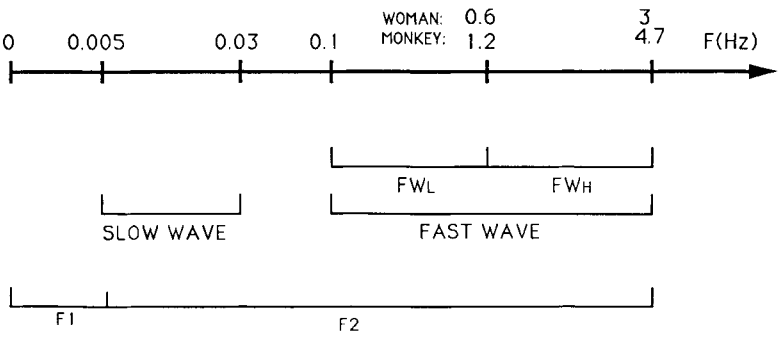

Fig. 4. Characteristics of electromyogram frequency content.

and the electrohysterogram is usually noted.[1, 88, 103-105] Both signals generally start at most 30 seconds before the intrauterine pressure increase.[87-91, 103-107] Only Mansour et al.,[104] studying monopolar electromyograms in the macaque, have specified that FW_L starts before the intrauterine pressure increase, whereas FW_H is restricted to the intrauterine pressure rising edge. This correlation reinforces the belief that electrohysterograms are genuine representatives of uterine activity, because they are temporally correlated with the myometrial electromyogram that precedes the intrauterine pressure. Thus, like the electromyogram, the electrohysterogram contains the electrical information that is at the origin of mechanical contraction.

Spectral characteristics. Although most authors have worked on temporal signals, some have tried to identify the intrinsic frequency components of an electromyogram burst. The frequency spectrum contains information about F2 variations and also to some extent F1, depending on the window width and the type of filtering. It seems reasonable to analyze the spectral content of the uterine electromyogram by making a distinction between the two main frequency areas (Fig. 4). F1 is representative of the periodic ocurrence of the bursts. During human parturition it corresponds to a maximum of three contractions per 10 minutes (i.e., maximum F1 = 0.005 Hz). F2 can be divided into two distinct activities: a slow wave that is mainly obtained with abdominal recordings and is likely caused by mechanical artifacts, ranging from 0.014 to 0.033 Hz, and a fast wave that is the frequency band representative of uterine activity. It can be recorded in all situations (myometrial or abdominal recordings, parturition or pregnancy). It contains two specific domains: a low-frequency (FW_L) domain present in any uterine electrical recording and a high-frequency (FW_H) domain related to efficient labor contractions. The slight difference in the frequency ranges for FW_L and FW_H between monkeys[103-105] and humans[106, 107] may be because the monkeys have smaller uteri and hence higher frequencies of cell firing rate.[127]

We stated earlier that the abdominal electrohysterogram theoretically contains the same information as the myometrial electromyogram, except for an attenuation of the high frequencies because of tissue filtering and for a high-pass filtering because of the bipolar recording mode. Recently, using spectral techniques such as power spectral density, Mansour et al.[103-105] demonstrated the similarities and the differences between electromyogram and electrohysterogram spectra resulting from filtering effects (Fig. 5). The temporal correlation and similar spectral content of the electromyogram and the electrohysterogram prove that electrohysterogram signals are unambiguously representative of uterine activity. The electrohysterogram has the advantage of being a noninvasive tool that could be used for detection and characterization of contractions in obstetric monitoring.

One of the most useful advantages from the obstetric viewpoint would be the ability to deduce contraction efficiency from the electromyogram signals. Contraction efficiency is mainly related to two different phenomena: action potential firing rate increase (associated with an increase in tension until tetanus occurs) and more fibers contracting simultaneously (associated with activity synchronization). Furthermore, because the strength of the contraction is related to the frequency of action potentials, the uterus can contract until tetanus if the frequency (F2) is high enough.[1] Many authors have observed in both myometrial and abdominal recordings an increase in F2 between pregnancy and parturition contractions (Tables I and II). Those who analyzed electrohysterogram power spectral density observed an increase in the FW_H power/FW_L power ratio[106, 107] associated with a shift of FW_L toward higher frequencies for efficient labor contractions.[106, 107] Nevertheless, further studies will be needed: first, to define the relation between FW_L and FW_H to determine whether these two frequency bands correspond to distinct physiologic events; second, to investigate the temporal relationship between the variation of F2 within a burst and the intrauterine pressure increase,

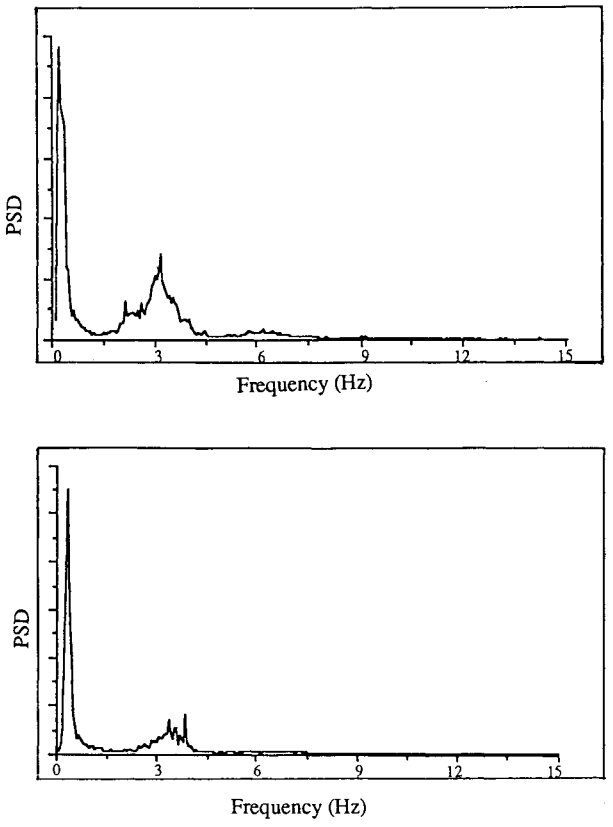

Fig. 5. *Upper tracing:* Averaged power spectral densities *(PSD)* of electromyogram signals obtained in pregnant monkeys, represented from DC to 10 Hz. Note the presence of FW_L (activity < 1.2 Hz) and FW_H (activity around 3 Hz). *Lower tracing:* Averaged power spectral densities of the corresponding electrohysterogram signals. Note on left side of abdominal FW_L clear cutoff from bipolar recording mode. Note that relative power of FW_H is lower on abdominal electrohysterogram because of the tissue filtering effect. (From Mansour S. Unpublished data.) Both tracings have similar scales.

using spectral tools such as time-frequency representations. It should then be possible to demonstrate a direct relationship between an increase in F2 and an increase in the slope of the intrauterine pressure rising edge.

Propagation. Contraction efficiency is related to the number of uterine cells simultaneously active because of faster electric propagation. Many authors have tried to investigate this propagation parameter. By analogy with striated muscle it first seemed of interest to identify the origin (pacemaker areas), a preferential direction, and the corresponding velocity for the propagation of events.

At the cellular level action potentials arising from a pacemaker cell are easily recognizable by the presence of a prepotential.[44] It is, however, doubtful that such specific prepotentials could be demonstrated at the electromyogram myometrial level. The baseline potential of an electrode always fluctuates in a range that would mask the low-frequency variations characteristic of prepotentials. Consequently, no specific pacemaker characterization could be expected at the whole organ level (myometrial or abdominal).

Using multielectrode recordings a number of authors have claimed that no specific areas could be identified as fixed pacemakers.[1, 86, 88, 89, 94, 98, 99] These assertions were justified by the fact that the first electrode to detect the electromyogram signal was different from one contraction to another. However, the conclusions drawn from mechanical propagation analysis are in disagreement, because they show the presence of a dominant pacemaker area in the fundus.[12, 128] Recently, by means of a video laparoscopy on rats during estrus, Crane and Martin[129] came to the conclusion that pacemaker cells are located in the cranial tip of each uterine horn and that most myometrial cells do not exhibit spontaneous pacemaker activity. This means that no anatomic pacemaker area has been localized to date. However, it is possible that, for yet unclarified reasons (e.g., difference of local densities in muscle fibers or cellular coupling) the apparent origin of contractions can remain functionally unchanged for several hours.

Synchronization between electrical and mechanical activities has been extensively used to investigate propagation. Activities have been found to be well synchronized during pregnancy and labor.[1, 72, 88, 89, 93, 94, 96] However, it is doubtful whether this analysis is pertinent to propagation, because electrical activity is always associated with a mechanical contraction, as stated above. Group propagation has also been quite extensively investigated, either by measuring the time difference between two electromyograms recorded at distinct but close electrodes,[1, 95, 96, 98, 103, 109, 112, 113] or by computing the intercorrelation of their envelopes.[103-105] The propagation velocities obtained ranged from 2 to 3 cm/sec,[1, 112-114] but there was no agreement concerning a preferential direction of propagation. Only Duchene et al.[115] computed a chronogram during the whole of parturition in one cynomolgus monkey. They demonstrated a specific order for the onset of electromyogram signals for their electrode configuration.

The question arises concerning the relevance of such measurements for propagation analysis. No specific pacemaker area has ever been found, because each uterine cell is a potential pacemaker. Furthermore, in primates the uterine muscular layers are not clearly distinct, unlike in the rat. Finally, gap junctions specifically appear at parturition, enhancing electrical propagation. In addition, these gap junctions can appear anywhere in the uterus, so that it is impossible to predict any specific preferential direction of propagation. Consequently, both the origin and propagation direction of uterine electrical activities are unknown at

any given moment, so that no propagation velocity can be computed. Although time intervals between two recording sites may sometimes be shorter at parturition than during pregnancy, there will be no direct relationship between time interval and propagation velocity. An analysis that needs further investigation in a large number of individuals is a systematic evaluation of the chronologic order of activities at different electrode locations. Differences may be expected between pregnancy and parturition, which would lead to the definition of a potential tool for qualitative propagation evaluation. Another possible approach would be to compute numerical models to relate cellular activity to macroscopic measurements. Such studies have been recently performed in the cardiac field.[130]

Another way to study propagation is to calculate the degree of similarities between two signals recorded by different electrodes during a specific contraction. This type of analysis involves cross correlations of the raw electromyograms, leading to the definition of linear propagation. This approach is unfortunately even more limited than group propagation for uterine muscle. Ideally, electrodes must be located along the fiber alignment, which is practically impossible to achieve in the primate uterus. Uterine cells are too small (several micrometers) with regard to the electrode size, and the uterus structure is not homogeneous. These limitations explain why Mansour et al.[103-105] did not manage to demonstrate any linear propagation in the cynomolgus monkey. Finally, the raw uterine electromyogram contains the trigger signal and the summation of all cell discharges, this cell activity being regenerated between the two recording sites. Consequently, two electrodes cannot record the same signal. The only propagating signal is the trigger, which is a slow membrane depolarization. So far nobody has attempted to extract and characterize the trigger component of the electromyogram uterine signal. In rodents Miller et al.[131] have shown in vitro in the uterine longitudinal layer that evoked spikes were propagated further and faster at parturition than during pregnancy in the same direction as the fibers. In primates where direct studies of linear propagation do not appear to be feasible, a possibility for investigating uterine synchronization would be to identify spectral modifications from enhanced coupling of firing cells. A better coupling between cells implies increased summation of electrical activities, which is reflected by modifications of the relative power in specific frequency bands.[121]

Comment

The uterine electromyogram, recorded either at the myometrial or abdominal level, provides reliable and useful information on uterine muscle behavior. Both electromyogram and electrohysterogram are shown to occur in phase with the intrauterine pressure increase. The abdominal electrohysterogram exhibits smaller amplitudes than the corresponding internally recorded electromyogram, but we have shown that amplitude should not be considered an absolute reference. Both types of electromyogram have almost the same spectra in which specific domains can be identified. The slow wave is mainly observed on abdominal recordings and is probably caused by mechanical artefacts such as skin stretching. It seems devoid of clear clinical interest. The fast wave has a frequency content that can be subdivided into two main domains whose limits seem to depend on species: a low-frequency band always present during both pregnancy and parturition contractions and a high-frequency band associated with efficient parturition contractions. The fast wave is the only relevant signal; it seems to be directly related to cellular activity (trigger and cell discharges) and is thus probably responsible for mechanical activity.

By applying spectral techniques such as cross correlation to electromyogram signal envelopes, it is possible to identify a group propagation. Onset times of electromyogram signals with respect to electrode location can be easily evaluated, but no certitudes concerning either group propagation origin or preferential propagation direction exist today. The classic spectral techniques, including cepstrum and coherence function, used to measure linear propagation have not so far provided any statistically reliable result when applied to the uterine electromyogram signal itself. No valid delay or propagation can thus be demonstrated, most likely because of the complex structure and organization of uterine muscle fibers.

Today the characteristics of the myometrial and abdominal uterine electromyogram are established. However, further investigations are needed to observe the modifications of these characteristics during pregnancy and at parturition. Human obstetric electrohysterogram monitoring requires further investigation to evaluate its prognostic value for premature labor detection. Systematic analysis of the chronologic order of activities at different electrode locations will have to be performed on a larger number of individuals, either at the myometrial or abdominal level. The expected differences could lead to the definition of a qualitative tool for group propagation evaluation. For analysis of uterine cell synchronization, linear propagation measurement has been proved to be inadequate because of the uterine structure. Additional investigations should be centered on the influence of the summation effect related to this synchronization and on the spectral characteristics of the electromyogram and the electrohysterogram. This will need a deeper analysis of the physiologic meanings of FW_L and FW_H, and of the variation already noted in their relative powers. The

uterine electromyogram and especially the noninvasive abdominal electrohysterogram appear to be very promising techniques for clinical or physiologic investigations of uterine activity.

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Appendix

Autocorrelation function. The autocorrelation function $R_{xx}(\tau)$ of a signal $x(t)$ is defined as:

$$R_{xx}(\tau) = \int_{-\infty}^{+\infty} x(t)x(t + \tau)dt$$

Power spectral density. For a signal $x(t)$, the power density spectrum $S_{xx}(f)$ is the Fourier Transform of its autocorrelation function $R_{xx}(\tau)$:

$$S_{xx}(f) = \int_{-\infty}^{+\infty} R_{xx}(\tau)\exp(-j2\pi f\tau)d\tau$$

where j is the complex operator.

It can be approached either by the Fourier Transform of an autocorrelation function estimate or from computation of the square module of the Fourier Transform of $x(t)$. The power density spectrum is the distribution representation of the spectral content of $x(t)$.

Cross correlation. The cross correlation $R_{xy}(\tau)$ of two signals $x(t)$ and $y(t)$ is defined as:

$$R_{xy}(\tau) = \int_{-\infty}^{+\infty} x(t)y(t + \tau)dt$$

It is a measurement of similarity [$R_{xy}(\tau)$ amplitude] and delay [$R_{xy}(\tau)$ peak position] between both signals.

Cross spectrum. The cross spectrum $S_{xy}(f)$ of two signals is defined as:

$$S_{xy}(f) = \int_{-\infty}^{+\infty} R_{xy}(\tau)\exp(-j2\pi f\tau)d\tau$$

Coherence function. The coherence function γ^2 between two signals $x(t)$ and $y(t)$ is a spectral function defined as:

$$\gamma^2 = \frac{|S_{xy}|^2}{S_{xx}\ S_{yy}}$$

The frequency bands where both signals are correlated can be deduced from this function.

Moving average modeling method. The moving average method consists of computing the transfer function of a filter where the output (an abdominal electrohysterogram) is deduced from the input (the corresponding myometrically recorded electromyogram) by means of a recursive formula.

Pattern recognition. It is sometimes useful to see whether samples can be classified with respect to some specific features. This classification is performed with pattern recognition methods where samples are expressed through representative parameters or statistical distributions.

Time-frequency representation. The power spectral density as defined here only holds theoretically for stationary signals. For nonstationary signals other techniques must be used to get a spectral description of the signal versus time. These techniques are known as time-frequency methods.