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Clinical Use of Electrohysterography During Term Labor: A Systematic Review on Diagnostic Value, Advantages, and Limitations

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Importance: Real-time electrohysterography (EHG)–based technologies have recently become available for uterine monitoring during term labor. Therefore, obstetricians need to be familiar with the diagnostic value, advantages, and limitations of using EHG.

Objective: The aims of this study were to determine the diagnostic value of EHG in comparison to (1) the intrauterine pressure catheter (IUPC), (2) the external tocodynamometer (TOCO), and (3) in case of maternal obesity; (4) to evaluate EHG from users’ and patients’ perspectives; and (5) to assess whether EHG can predict labor outcome.

Evidence Acquisition: A systematic review was performed in the MEDLINE, EMBASE, and Cochrane library in October 2017 resulting in 209 eligible records, of which 20 were included.

Results: A high sensitivity for contraction detection was achieved by EHG (range, 86.0%–98.0%), which was significantly better than TOCO (range, 46.0%–73.6%). Electrohysterography also enhanced external monitoring in case of maternal obesity. The contraction frequency detected by EHG was on average 0.3 to 0.9 per 10 minutes higher compared with IUPC, which resulted in a positive predictive value of 78.7% to 92.0%. When comparing EHG tocograms with IUPC traces, an underestimation of the amplitude existed despite that patient-specific EHG amplitudes have been mitigated by amplitude normalization. Obstetricians evaluated EHG tocograms as better interpretable and more adequate than TOCO. Finally, potential EHG parameters that could predict a vaginal delivery were a predominant fundal direction and a lower peak frequency.

Conclusions and Relevance: Electrohysterography enhances external uterine monitoring of both nonobese and obese women. Obstetricians consider EHG as better interpretable; however, they need to be aware of the higher contraction frequency detected by EHG and of the amplitude mismatch with intrauterine pressure measurements.

Target Audience: Obstetricians and gynecologists, family physicians.

Learning Objectives: After completing this activity, the learner should be better able to interpret the physiology of uterine contractions, relate the diagnostic value of electrohysterography (EHG) traces to intrauterine all authors, faculty, and staff in a position to control the content of this CME activity and their spouses/life partners (if any) have disclosed that they have no financial relationships with, or financial interests in, any commercial organizations pertaining to this educational activity.

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Term labor is characterized by regular uterine contractions leading to cervical dilation. Throughout labor, these uterine contractions need to be measured to allow monitoring of labor progress and support labor management, especially oxytocin adjustments. Moreover, the fetal heart rate (FHR) pattern in relation to uterine contractions provides important information on the fetal well-being, as contractions cause transient reduction of the uteroplacental blood flow. The fetal response to this temporary suboptimal condition can reveal a compromised oxygenation status. In addition, excessive uterine activity should be prevented during labor because it can induce fetal distress. Because of the increasing prevalence of labor induction and augmentation, the sensitivity of TOCO is adversely influenced by maternal position and excessive subcutaneous tissues (obesity). Therefore, the currently available TOCO and IUPC are not capable of monitoring uterine contractions leading to cervical dilation. Throughout labor, EHG reflects the root cause of uterine contractions. While the TOCO indirectly measures uterine activity by responding to external abdominal deformations, EHG reflects the root cause of uterine contractions. As compared with TOCO, the reliability of EHG measurements is expected to be less affected by maternal position and excessive subcutaneous tissues (obesity). In addition, EHG is noninvasive and does not require ruptured membranes as with IUPC. However, especially during the second stage of labor, EHG might be more exposed to artifacts due to maternal (pushing) movements, which could negatively influence its diagnostic values. Furthermore, the costs of EHG are higher than TOCO because of the disposable sensors.

The potential applications of EHG-based technologies in pregnancy and labor are extensive. Clinical applications include differentiating between true and false labor (eg, to predict preterm labor and to optimize the management of pregnant women at term without cervical dilation) and improving uterine monitoring during labor (eg, to prevent nonprogressive labor or fetal distress and thereby to reduce the cesarean delivery rate for these indications). Considering the recent launch of several commercial systems aiming at providing real-time EHG-based tocograms, we expect the assessment of uterine contractions during term labor to be among the first clinical applications of EHG-based technologies. In this review, we appraise the diagnostic value, advantages, and limitations that obstetric caregivers should be familiar with when applying EHG as uterine monitoring technique during term labor. After reading this review, obstetric caregivers should be better able to compare the test characteristics of EHG with those of conventional methods (ie, IUPC and TOCO) and therefore be aware of the antepartum and intrapartum circumstances in which EHG could provide accessory information for optimal dedicated interventions.

**Physiology**

Uterine contractions originate from the electrical activity of the myometrial smooth muscle cells and result in an increase in the intrauterine pressure (IUP). However, the exact mechanism underlying the electrical origin of uterine contractility is still unclear.
In comparison to other organs, the electrophysiology of
the uterus reveals an exceptional complexity.15,18

The myometrium is composed of smooth muscle
fibers, which are relatively small cells that slowly
contract and have a high regeneration capability.17
In addition, the uterus is a myogenic organ, which
means that the myometrium is able to contract without
nervous or hormonal inputs.12 It is not clear whether
a pacemaker mechanism exists.15 Dedicated pace-
maker cells or areas with pacemaker activity have been
researched.15,19 However, there is evidence supporting
the theory that any uterine cell can potentially become
a pacemaker cell or can be excited by a neighboring
cell.15,20

In general, smooth muscle cells highly depend on
calcium influx, which explains why calcium-channel
blockers are effective as uterine tocolytic drugs.21 The
intracellular calcium concentration is low when smooth
cells are at rest. As action potentials propagate through
a myometrial cell, depolarization causes an inflow of
calcium ions through the cell membrane by opening
inghtage-dependent calcium channels.13,16 These elec-
trical discharges appear as intermittent bursts of spike-like
action potentials. A contraction can be initiated by a single
spike; however, multiple, coordinated spikes are needed
for contractions leading to true labor.13,22 This may ex-
plain why frequent contractions do not necessarily lead
to imminent labor23,24 and why burst energy (ie, the prod-
ct of burst duration and sum of power components)
seems an adequate prognostic factor to discriminate
between true and false labor.12

Uterine contractions are physiological events during
all stages of pregnancy. From the 20th week, the so-
called Braxton Hicks contractions appear that have an
irregular pattern and do not result in cervical changes.25
Throughout pregnancy, the hormone progesterone
inhibits uterine conductivity, which is therefore being
applied as prevention of premature birth. Toward the
end of pregnancy, biochemical changes in uterine tissue
occur in preparation for labor, resulting in changes of
the bioelectrical uterine activity.26 Myometrial cells
are electrically coupled by gap junctions.17 These are
composed of proteins that form channels of low resistance
between the myometrial cells, thus improving electrical
conductivity.16 Hormones, such as estrogens, oxytocin,
and prostaglandins, improve electrical propagation due
to stimulating the formation of these gap junctions and
increase the excitability of the uterine muscle cells.20,27
Increased uterine volume in case of twin pregnancies,
polyhydramnios, or full-term pregnancy may also im-
prove uterine electrical activity by mechanical activation
of stretch receptors in the myometrial wall to syncho-
nize activity and contraction.20,28 In the end, this priming
process becomes irreversible and leads to labor. The
uterine activity is then fully propagated and coordinated
to the whole uterus to enable fetal expulsion.20

**ELECTROHYSTEROGRAPHY**

Electrohysterography is a noninvasive technique that
measures the electrical signals of the uterine muscle.
Electrohysterography evaluates the electrical informa-
tion that is the origin of mechanical contractions.29 Al-
ready from the 19th week of gestation, EHG can be
measured by abdominal electrodes.30 Studies in humans
and animals show that each contraction is accompa-
nied by a burst of action potentials, which starts slightly
earlier than the mechanical contraction and stops before
the uterus relaxes.13,19,31

**TECHNICAL ASPECTS**

Different applications for the analysis of uterine elec-
trical activity are proposed, ranging from pregnancy
monitoring for, for example, preterm delivery prediction,
to labor monitoring by, for example, IUP estimation.

Uterine electrical activity can be recorded noninva-
sively by surface electrodes. Animal studies evaluating
EHG signals obtained directly from the uterine surface
have demonstrated that these abdominal recordings
accurately measure uterine biopotentials,13,26,32 Type
and number of employed electrodes widely vary in
the literature, depending on the specific objective of
EHG analysis.

For IUP estimation, contact silver–silver chloride
electrodes are mostly used with contact surface areas
in the order of 2 to 3 cm². The good contact provided
by silver–silver chloride electrodes in combination
with relative large surface areas show a good signal
quality and a sufficient spatial resolution for this spe-
cific application.33,34

To measure any biopotential, a minimum of 2 elec-
trodes is needed as any voltage is derived as the dif-
ference between the signals at 2 locations (active and
reference electrodes, respectively). To estimate the IUP,
a single channel (ie, 2 electrodes) is sufficient. However,
in several protocols, the use of electrode arrays is
motivated by an increased robustness or by the need
to investigate additional parameters such as the optimal
electrode location or the propagation properties of the
EHG signal.35,37

Abdominal biopotential measurements during preg-
nancy and labor do not reflect uterine activity alone.
Undesired signals such as the skeletal muscle electro-
myogram, the mother's electrocardiogram (ECG), and
movement artifacts due to, for example, respiration,
are also recorded by abdominal electrodes in addition
to the desired EHG signal. A significant attenuation of these undesired signals is obtained by bipolar measurements (ie, by placing active and reference electrodes close to each other on the abdomen).\(^\text{15}\)

To improve the signal quality and minimize the influence of undesired signals on the IUP estimation, a variety of electrode locations and interelectrode distances have been proposed and tested. For IUP estimation, interelectrode distances between 8 and 14 cm seem to provide the best signal quality.\(^\text{38}\) Comparison of several types of electrodes and locations has been performed by Alberola-Rubio et al.\(^\text{33}\) revealing best results with electrodes over the median axis.

Skin preparation by abrasive paste for skin impedance reduction is also usually performed prior to sensor positioning, in order to reduce the effects of interferences and artifacts.\(^\text{34}\) The signal is usually amplified and digitized by dedicated systems that also provide the possibility of storing the data digitally for (off-line) processing and estimation of the relevant parameters.

Filtering or selection of a specific frequency band for EHG signal analysis is a common choice to further reduce the effect of artifacts in EHG signal processing. In fact, the EHG signal is characterized by a low-frequency content, usually less than 5 Hz, which is typical of biopotentials recorded from smooth muscles. Furthermore, respiration and related movement artifacts in pregnancy lie below 0.3 Hz, whereas the heart rate is above 0.8 Hz.\(^\text{36}\) Therefore, IUP estimates are often derived from EHG measurements in the frequency band between 0.3 and 0.8 to 1.0 Hz. Dedicated algorithms have been also developed for the removal of specific unwanted biopotentials such as the maternal ECG.\(^\text{39}\)

Depending on the application of interest, different parameters can be extracted from the EHG signal. Promising features for the prediction of preterm birth are related to the frequency content of the EHG signal.\(^\text{32,40-44}\) Studies on parameters related to the EHG signal amplitude, for example, root mean square (RMS) value, have shown more controversial results.\(^\text{44,45}\) More recently, estimation of the EHG conduction velocity has been proposed to predict (preterm) delivery with promising results.\(^\text{24,46}\)

For estimation of the IUP from the EHG signal, methods based on an estimate of the EHG signal amplitude, for example, by focusing on the RMS value\(^\text{47}\) of the filtered signal or the signal energy, have been mostly used. The results of these estimations have been compared either with the internal IUPC or with the external TOCO measurements. For estimating the EHG signal energy, the Teager Energy\(^\text{38}\) has been proposed as an alternative to time-frequency analysis\(^\text{36}\) for a reduced complexity. Optimal linear filtering\(^\text{48}\) has been also proposed to derive an estimation of the IUP trace and compared with the simultaneous invasive measurement. On the technical point of view, the accuracy of these methods has been evaluated based on quality measures such as the correlation coefficient and mean square error between the estimate and the reference method.\(^\text{36,38,48}\)

Although a direct relationship between these quality measures and the specificity (sensitivity) of the EHG-based estimate does not exist, a high correlation with the criterion standard can be related to an accurate detection of the contraction events (contraction frequency, timing, and counting). Low mean square errors are, instead, indicative of good estimations of pressure amplitude. Toward clinical usability of these methods, dedicated algorithms for uterine contraction monitoring have been also proposed.\(^\text{47,49}\)

**MATERIALS AND METHODS**

**Sources**

The aims of this systematic review were to appraise the diagnostic value, advantages, and limitations of EHG for uterine contraction monitoring during term labor and to compare these test characteristics to TOCO and IUPC. This study included the evaluation of EHG as a potential method for contraction detection and validated by IUP measurement, which has been considered as the current criterion standard. Furthermore, the performance of EHG-based diagnosis was compared with the diagnostic value of TOCO, which has been the most applied method. The diagnostic values of EHG-based methods and TOCO were evaluated in obese pregnant women as well. Patients’ obesity has been, in fact, one of the major challenges in labor care and diagnostics. Furthermore, to appraise uterine monitoring techniques from all perspectives, research on users’ and patients’ experiences was reviewed and discussed. Finally, this review explored the potential of another innovative application of EHG, namely, prediction of delivery mode (ie, vaginal or cesarean).

We systematically searched MEDLINE, EMBASE, and the Cochrane Library in October 2017 using the following standardized MeSH terms “pregnant women,” “term birth,” “obstetric labor,” “obstetric delivery,” “electrohysterography,” “electrohysterogram,” “uterine electromyography,” “uterine monitoring,” “uterine contraction,” “external tocodynamometer,” “intra-uterine pressure catheter,” and related free terms presented in the title and abstract. The filter “English language” was applied for this study.
Study Selection

A total of 167 articles have been systematically identified after removing 42 duplicates. To assess eligibility of the studies, 2 authors (M.W.C.V., C.R.) appraised the extracted studies. The flowchart of the search strategy and selection is shown in Figure 1. We selected studies meeting the following inclusion criteria:

- Pregnant women during term labor (gestational age ≥37 weeks),
- Recording of EHG with contact electrodes on the maternal abdomen, and
- Analysis of EHG as uterine monitoring technique, including one of these topics:
  1. The diagnostic value of EHG in comparison to IUPC,
  2. The diagnostic value of EHG in comparison to TOCO,
  3. Uterine monitoring in obese women by EHG,
  4. Users' and patients' appraisal of EHG compared with TOCO and IUPC, and
  5. EHG for prediction of the delivery mode (ie, vaginal or cesarean).

We excluded (technical) reviews, modeling methods, guidelines, conference papers, case reports, and duplicates.

RESULTS

Description of the Reviewed Studies

The characteristics of the 20 studies included in this review are listed in Table 1, which incorporates the inclusion and exclusion criteria, comparison method, device and software, number and type of derivations, measurement of skin impedance, signal duration per patient and analysis, outcome parameters, and ethical considerations. In all studies, EHG was monitored by abdominal electrodes. The number of electrodes ranged from 2 to 9 electrodes in either a monopolar or bipolar configuration. However, not all studies provided information on the derivation of the active measuring electrodes and/or ground electrode, which was described as such in the column “Number and Type of Derivations” in Table 1.12,51,52,54,56,63,64 An interelectrode distance between 2.5 and 12 cm was reported or was adjusted per patient. The average measurement duration per patient varied from 22 minutes to several hours.

The QUADAS-2 scale has been applied for quality assessment of the primary diagnostic accuracy studies, which is shown in Table 2. The general risk of bias was considered low, as most studies compared EHG with simultaneously recorded IUPC, which is the criterion standard for uterine monitoring. Four studies (partially) compared EHG directly with TOCO without IUPC,47,53,59,62 which is considered suboptimal because TOCO has the tendency to underestimate the uterine contraction frequency.55,57,60,61 Furthermore, the overall applicability of the study participants was satisfactory. Most studies included pregnant women in labor at term. Only 3 studies included both term and preterm labor.52,55,59 Furthermore, Jezewski et al.47 included women during 24 hours before labor.

The extracted test characteristics have been presented in Table 3. A 2-sided P < 0.05 was considered statistically significant.

Clinical Questions

The results of the 20 studies were presented according to the following clinical questions:

- What is the diagnostic value of EHG-based contraction detection relative to IUPC?
- Can EHG improve external uterine monitoring in comparison to TOCO?
- Is EHG capable of improving external uterine monitoring in obese parturients?
- What are the users' and patients' experiences on EHG-based uterine monitoring?
- Can EHG provide parameters for predicting labor outcome, that is, vaginal or cesarean delivery?

**Question 1: What Is the Diagnostic Value of EHG-Based Contraction Detection Relative to IUPC?**

For a direct comparison of EHG with IUPC, most studies translated EHG into an “IUP-estimated” waveform...
<table>
<thead>
<tr>
<th>Study</th>
<th>N</th>
<th>Inclusion Criteria</th>
<th>Exclusion Criteria</th>
<th>Comparison Method</th>
<th>Device and Software</th>
<th>Number and Type of Derivations</th>
<th>Measurement Skin Impedance</th>
<th>Skin Impedance per Patient and Analysis</th>
<th>Signal Duration</th>
<th>Outcome Parameters</th>
<th>Ethical Considerations</th>
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</thead>
<tbody>
<tr>
<td>Maul et al, 13 2003</td>
<td>13</td>
<td>Term labor IUPC for obstetric indications</td>
<td>Not described</td>
<td>IUPC</td>
<td>Chart 4.0.3 software; AD Instruments, Castle Hill, Australia</td>
<td>4 active electrodes, unspecified derivation</td>
<td>Not described</td>
<td>45-min minimum duration; random selection of 5 contractions, signal criteria not described</td>
<td></td>
<td>Correlation between IUP and EHG</td>
<td>+ Study approval, informed consent</td>
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<tr>
<td>Euliano et al, 50 2006</td>
<td>14</td>
<td>Term labor; singleton fetus; cephalic presentation; IUPC for obstetric indications</td>
<td>Not described</td>
<td>IUPC</td>
<td>Amplifier for fetal ECG extraction, unspecified producer</td>
<td>8 Monopolar signals</td>
<td>&lt;10 kΩ</td>
<td>49-min average duration; 68 good 10-min traces; signal criteria for contraction detection MVU calculation by blinded reviewers</td>
<td>Sensitivity, PPV, contraction frequency, contraction duration, waveform correlation of IUP and EHG for MVUs and AUC</td>
<td>+ Informed consent; no description of study approval; first author’s husband is president, and another author is employee of Convergent Engineering. Both are listed on patents</td>
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<tr>
<td>Rabotti et al, 36 2008</td>
<td>9</td>
<td>Term labor IUPC for obstetric indications</td>
<td>Not described</td>
<td>IUPC</td>
<td>M-PAQ amplifier; Maastricht Instruments Ltd, the Netherlands</td>
<td>5 Bipolar signals</td>
<td>Not described</td>
<td>22- to 90-min range duration, 3 EHG algorithms tested</td>
<td>Correlation between IUP and EHG RMSE (mm Hg)</td>
<td>+ Study approval, informed consent</td>
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<tr>
<td>Jacod et al, 51 2010</td>
<td>32</td>
<td>Term labor IUPC for obstetric indications</td>
<td>Not described</td>
<td>IUPC</td>
<td>ANZ4 recorder; Monica Healthcare, Nottingham, United Kingdom</td>
<td>4 Active electrodes, unspecified derivation</td>
<td>&lt;5 kV</td>
<td>67-min median duration, automated contraction detection algorithm</td>
<td>Sensitivity, PPV, duration correlation, amplitude correlation, correlation with BMI</td>
<td>+ Study approval, informed consent</td>
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<tr>
<td>Name</td>
<td>Year</td>
<td>Labor Type</td>
<td>GA Range</td>
<td>Singleton</td>
<td>Fetal Abnormality</td>
<td>Technical Issues</td>
<td>IUPC Devices</td>
<td>Electrodes</td>
<td>Duration</td>
<td>Study Approval, Consent</td>
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<tr>
<td>Haran et al.</td>
<td>2012</td>
<td>Term and preterm labor</td>
<td>32–42 wk, average 39 wk</td>
<td>Singleton fetus</td>
<td>IUPC functioning</td>
<td>OB Tools Ltd, Migdal Ha'Emek, Israel</td>
<td>EUM monitor</td>
<td>9 unspecified derivation</td>
<td>30-min</td>
<td>1 blinded reviewer</td>
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<td>Rooijakkers et al.</td>
<td>2014</td>
<td>Term labor</td>
<td>Not described</td>
<td>IUPC</td>
<td>M-PAQ amplifier, Maastricht Instruments Ltd</td>
<td>Bipolar signals</td>
<td>Not described</td>
<td>26- to 138-min range duration</td>
<td>Correlation between IUP and EHG for AUC</td>
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<td>Jezewski et al.</td>
<td>2005</td>
<td>Within 24 h from term labor</td>
<td>Not described</td>
<td>TOCO</td>
<td>General-use amplifier, unspecified producer</td>
<td>Bipolar signals</td>
<td>Not described</td>
<td>40-min average duration</td>
<td>Consistent contractions, CCI, contraction onset, rise time, and duration, amplitude correlation, waveform correlation of TOCO with EHG for AUC</td>
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<tr>
<td>Euliano et al.</td>
<td>2007</td>
<td>Term labor BMI &gt;34 kg/m²</td>
<td>IUPC not functioning (n = 1)</td>
<td>IUPC or TOCO</td>
<td>Amplifier for fetal ECG extraction, unspecified producer</td>
<td>Monopolar signals</td>
<td>&lt;10 kΩ</td>
<td>2 × 30-min duration before and after IUPC placement, automated contraction detection</td>
<td>Sensitivity, PPV, consistent contractions, CCI, contraction duration, correlation with BMI</td>
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<tr>
<th>Study</th>
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<th>Comparison Method</th>
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<th>Number and Type of Derivations</th>
<th>Measurement Skin Impedance</th>
<th>Measurement Signal Duration per Patient and Analysis</th>
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<th>Ethical Considerations</th>
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<tr>
<td>Hayes-Gill</td>
<td>74</td>
<td>Term labor, singleton fetus, cephalic presentation, IUPC for obstetric indications</td>
<td>No IUPC (n = 35), technical issues (n = 25), measurement &lt;30 min (n = 4), fetal abnormality/malpresentation</td>
<td>IUPC and TOCO</td>
<td>AN24 recorder; Monica Healthcare</td>
<td>5 Electrodes, unspecified derivation</td>
<td>Not described</td>
<td>261-min average duration, automated identification of interpretable IUPC and contraction detection, nurses checked TOCO each 20–30 min</td>
<td>Sensitivity, PPV, false-positive rate, positive percent agreement; contraction frequency, contraction peak timing</td>
<td>+ Study approval, +informed consent; 1 author is shareholder, and 4 authors are or have been consultants of Monica or Philips Healthcare</td>
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<td>Alberola-Rubio</td>
<td>22</td>
<td>Term labor, singleton fetus</td>
<td>Not described</td>
<td>IUPC and TOCO</td>
<td>Biopac ECG 100C; Biopac Systems Inc, USA</td>
<td>5 Monopolar, 2 annular, 1 Laplacian from the 5 monopolar signals</td>
<td>Not described</td>
<td>30- to 180-min range duration; contraction detection by 2 of 3 experts</td>
<td>Consistent contractions, CCI</td>
<td>+ Study approval, +informed consent</td>
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<td>Euliano</td>
<td>59</td>
<td>Term and preterm labor; GA: range 33–42 wk, average 39 wk; singleton fetus; cephalic presentation; IUPC for obstetric indications or study purposes</td>
<td>Uterine scar, vaginal bleeding, contraindication for IUPC placement, hardware failure (n = 12), inadequate duration (n = 2)</td>
<td>IUPC and TOCO</td>
<td>General use amplifier, unspecified producer</td>
<td>4 Monopolar signals &lt;10 kΩ</td>
<td>137-min average duration; signal criteria for contraction detection</td>
<td>Sensitivity, PPV, consistent contractions, CCI, contraction peak/ onset-offset; contraction duration; waveform correlation IUP and EHG; obesity analysis: BMI ≥35 kg/m²; correlation with BMI</td>
<td>+ Study approval, +informed consent; some authors have patents on the described technology and/or are employees of Convergent Engineering</td>
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<tr>
<td>Author(s)</td>
<td>Year</td>
<td>Study Type</td>
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<tr>
<td>Cohen and Hayes-Gill</td>
<td>2016</td>
<td>Term labor</td>
<td>BMI not calculated (n = 1)</td>
<td>IUPC and TOCO</td>
<td>243- to 291-min</td>
<td>Sensitivity, PPV, false-positive rate, positive percent agreement, contraction frequency, correlation with BMI</td>
<td>+ Study approval, − informed consent not described; funding by Monica Healthcare; 1 author is a paid consultant, and 1 author is shareholder director of the company</td>
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<tr>
<td>Vlemminx et al.</td>
<td>2017</td>
<td>Term labor</td>
<td>Infections, placenta/ vasa previa, fetal distress, dermatologic abdominal diseases, measurement &lt;30 min (n = 1)</td>
<td>IUPC and TOCO</td>
<td>105-min</td>
<td>Sensitivity, PPV, false-positive ratio, false-negative ratio, CCI, contraction frequency, obesity analysis; BMI ≥ 30 kg/m², comparison 1st/2nd stage</td>
<td>+ Study approval, − informed consent; one of the authors is initiator of Nemo Healthcare. This author has no financial interest in the company</td>
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<tr>
<td>Vlemminx et al.</td>
<td>2018</td>
<td>Term labor</td>
<td>Infections, placenta/ vasa previa, fetal distress, dermatologic abdominal diseases, measurement &lt;30 min (n = 1)</td>
<td>IUPC and TOCO</td>
<td>101- to 112-min</td>
<td>Sensitivity, PPV, CCI, CORRELATION with BMI and abdominal circumference</td>
<td>+ Study approval, − informed consent; one of the authors is initiator of Nemo Healthcare. This author has no financial interest in the company</td>
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<tr>
<th>Study</th>
<th>N</th>
<th>Inclusion Criteria</th>
<th>Exclusion Criteria</th>
<th>Comparison Method</th>
<th>Device and Software</th>
<th>Number and Type of Derivations</th>
<th>Measurement Skin Impedance</th>
<th>Signal Duration per Patient and Analysis</th>
<th>Outcome Parameters</th>
<th>Ethical Considerations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reinhard et al. 11</td>
<td>144</td>
<td>Term and preterm labor, GA: range 35–42 wk, average 39 wk, singleton fetus</td>
<td>Not described</td>
<td>TOCO</td>
<td>AN24 monitor; Monica Healthcare</td>
<td>1 Bipolar signal</td>
<td>Not described</td>
<td>Average duration: 264 min in 1st stage (n = 149), 48 min in 2nd stage (n = 93), criteria for adequate and inadequate tracings, random quality assessment by 4 blinded gynecologists</td>
<td>Interpretability: adequate or inadequate, assessment scale: (1) easy, (2) intermediate, (3) difficult contraction frequency, contraction interpretation, positive percent agreement, sensitivity, PPV, false-positive ratio, false-negative ratio, contraction timing</td>
<td>- Informed consent; study approval not described; 1 author is director of Monica Healthcare</td>
</tr>
<tr>
<td>Hadar et al. 60</td>
<td>43</td>
<td>Term labor, singleton fetus, IUPC for obstetric indications</td>
<td>Withdrawal informed consent (n = 2)</td>
<td>IUPC and TOCO</td>
<td>EUM 100 monitor; OB-Tools Ltd</td>
<td>9 Monopolar signals</td>
<td>Not described</td>
<td>90-min Average duration: 2 x 30 min 1st stage and 1 x 30 min 2nd stage; 3 blinded independent expert reviewers</td>
<td>Interpretability: interpretable tracings, positive percent agreement, sensitivity, PPV, false-positive ratio, false-negative ratio, contraction timing</td>
<td>+ Study approval, +informed consent</td>
</tr>
<tr>
<td>Euliano et al. 61</td>
<td>105</td>
<td>Term labor, singleton fetus, cephalic presentation, IUPC for obstetric indications</td>
<td>Vaginal bleeding, uterine scar, signs of intrauterine infection</td>
<td>UPC and TOCO</td>
<td>General use amplifier, unspecified producer</td>
<td>4 Monopolar signals</td>
<td>&lt;10 kΩ</td>
<td>Average duration: 51 min in 1st stage (n = 102), 58 min in 2nd stage (n = 31); Web-based application; 4 blinded clinicians (2 obstetricians and 2 nurses)</td>
<td>Interpretability, positive percent agreement, consistent contractions, sensitivity, false-positive ratio, false-negative ratio, contraction timing, obesity analysis: BMI ≥30 kg/m²</td>
<td>+ Study approval, +informed consent; some authors have patents on the described technology and/or are employees of the company</td>
</tr>
<tr>
<td>Study</td>
<td>Case-control study</td>
<td>Uterine scar, other reasons for cesarean delivery than labor arrest, unusable data (n = 2), lack of matching controls (n = 2)</td>
<td>IUPEC in 11/12 of cesarean delivery group, other 25 TOCO</td>
<td>Amplifier for fetal ECG extraction, unspecified producer</td>
<td>8 Monopolar signals</td>
<td>&lt;10 kΩ</td>
<td>30-min duration, contraction subdivided in T1 = onset to peak, T2 = peak back to baseline; contractions patterns in vertical direction (1) toward lower uterine segment, (2) toward the fundus</td>
<td>Comparison 2 groups: (1) cesarean delivery for labor arrest, ≥5 cm (n = 12), (2) vaginal delivery, dilation &gt;1 cm/h (n = 24); analyses of the vertical direction of the uterine activity center</td>
<td>+ Study approval, + informed consent; some authors are employees of Convergent Engineering, and some authors are listed on patents filed for some of described technologies</td>
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<tr>
<td>Euliano et al, 2009</td>
<td>36 Case-control study: cesarean delivery for term labor arrest vs vaginal delivery; singleton fetus; cephalic presentation; matching 1:2, for GA, BMI, parity, induction, comparable dilation</td>
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</table>
| Vasak et al, 2013 | 119 Term labor, nulliparous, spontaneous onset, singleton fetus, cephalic presentation | None | AN24 monitor; Monica Healthcare | 4 Active electrodes, unspecified derivation | <5 kΩ | 219- to 370-min average duration; EHG PDS computation | Power density spectrum in (1) vaginal delivery without labor augmentation (n = 32), (2) vaginal delivery with labor augmentation (n = 73), (3) cesarean delivery for 1st stage labor arrest (n = 14); subanalysis comparing before/after oxytocin | + Study approval, + informed consent; monitors were provided by Monica Healthcare, as an unrestricted grant; + no conflicts of interest | (Continued on next page)
<table>
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<tr>
<th>Study</th>
<th>N</th>
<th>Inclusion Criteria</th>
<th>Exclusion Criteria</th>
<th>Comparison Method</th>
<th>Device and Software</th>
<th>Number and Type of Derivations</th>
<th>Measurement Skin Impedance</th>
<th>Signal Duration per Patient and Analysis</th>
<th>Outcome Parameters</th>
<th>Ethical Considerations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vasak et al.64, 2017</td>
<td>141</td>
<td>Term labor, nulliparous, induction of labor, singleton fetus, cephalic presentation</td>
<td>Suspected congenital or chromosomal abnormalities</td>
<td>None</td>
<td>AN24 monitor; Monica Healthcare</td>
<td>4 Active electrodes, unspecified derivation</td>
<td>&lt;5 kΩ</td>
<td>219- to 602-min average duration; EHG PDS computation</td>
<td>Power density spectrum in (1) vaginal delivery without oxytocin (n = 10), (2) vaginal delivery with oxytocin (n = 113), (3) cesarean delivery for 1st stage labor arrest (n = 18), (4) spontaneous onset of labor vaginal delivery without oxytocin (n = 32)</td>
<td>+ Study approval, +informed consent; monitors were provided by Monica Healthcare, as an unrestricted grant; + no conflicts of interest</td>
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GA indicates gestational age; RMSE, RMS error.
obtained from dedicated methods for EHG analysis. Therefore, readers should be aware that the diagnostic value of EHG in most studies was based on an IUP-estimated waveform.

The EHG diagnostic parameters of interest were sensitivity, positive predictive value (PPV), false PPV, false negative predictive value (false NPV), and the Contraction Consistency Index (CCI). The sensitivity of EHG was derived as the capability of this method to capture those contractions that were detected with the criterion standard IUPC. The PPV and false PPV represented the percentage of contractions in the EHG tocogram, which are detected or nondetected by IUPC, respectively. The false NPV represented the percentage of contractions missing in the EHG tocogram, which were monitored by IUPC. In addition, the CCI (proposed by Jezewski et al \(^{47}\)) entailed a comparison index with IUPC. A low CCI means that EHG either overestimates or underestimates the amount of contractions. Furthermore, the contraction frequency of EHG was evaluated in comparison to IUPC. Per study we calculated the average contraction frequency per 10 minutes of each method and the average difference of the contraction frequency between IUPC, EHG, and TOCO.

Further, the IUP-estimated waveforms of EHG were compared with IUPC waveforms regarding the contraction onset, contraction offset, contraction duration, contraction peak timing, and correlation with IUP. Most studies applied a 10% baseline to represent the onset and offset of contractions. The contraction duration

<table>
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<tr>
<th>Risk of Bias</th>
<th>Applicability Concerns</th>
<th>Flow and Timing</th>
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<tbody>
<tr>
<td>Patient Selection</td>
<td>Index Test</td>
<td>Reference Standard</td>
</tr>
<tr>
<td>Term Labor</td>
<td>EHG</td>
<td>IUPC</td>
</tr>
<tr>
<td>Maul et al., (^{12}) 2004</td>
<td>+</td>
<td>Ø 5 contractions</td>
</tr>
<tr>
<td>Jezewski et al., (^{47}) 2005</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Euliano et al., (^{50}) 2006</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Euliano et al., (^{33}) 2007</td>
<td>+</td>
<td>BMI &gt;34</td>
</tr>
<tr>
<td>Rabotti et al., (^{36}) 2008</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Euliano et al., (^{52}) 2009</td>
<td>Ø Matching</td>
<td>+</td>
</tr>
<tr>
<td>Jacod et al., (^{51}) 2010</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Reinhard et al., (^{59}) 2011</td>
<td>+</td>
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<tr>
<td>Han et al., (^{55}) 2012</td>
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<tr>
<td>Hayes Gill 2012</td>
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<tr>
<td>Alovera-Rubio et al., (^{33}) 2013</td>
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<tr>
<td>Euliano et al., (^{35}) 2013</td>
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<tr>
<td>Vasak et al., (^{63}) 2013</td>
<td>+</td>
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</tr>
<tr>
<td>Cohen and Hayes-Gill (^{56}) 2014</td>
<td>+</td>
<td>+</td>
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<tr>
<td>Rooijakkers et al., (^{38}) 2015</td>
<td>+</td>
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<tr>
<td>Hadar et al., (^{50}) 2016</td>
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<td>Euliano et al., (^{35}) 2016</td>
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<tr>
<td>Vasak et al., (^{64}) 2017</td>
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<tr>
<td>Vlemminx et al., (^{57}) 2017</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Vlemminx et al., (^{58}) 2018</td>
<td>+</td>
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</table>

+ , Low risk; Ø, high risk.

GA indicates gestational age in weeks.

TABLE 3 Diagnostic Characteristics of EHG and TOCO for Uterine Contraction Detection During Term Labor

<table>
<thead>
<tr>
<th>Diagnostic Parameter</th>
<th>EHG (Range)</th>
<th>TOCO (Range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity, %</td>
<td>86.0–98.0</td>
<td>46.0–73.6</td>
</tr>
<tr>
<td>Sensitivity in obese women, %</td>
<td>82.0–97.2</td>
<td>45.0–65.3</td>
</tr>
<tr>
<td>PPV, %</td>
<td>78.7–92.0</td>
<td>67.2–86.0</td>
</tr>
<tr>
<td>PPV in obese women, %</td>
<td>79.2–90.6</td>
<td>56.2–88.0</td>
</tr>
<tr>
<td>CCI, %</td>
<td>75.4–88.0</td>
<td>65.1–69.0</td>
</tr>
<tr>
<td>CCI in obese women, %</td>
<td>82.0–94.0</td>
<td>50.8–60.0</td>
</tr>
<tr>
<td>False PPV, %</td>
<td>8.0–21.3</td>
<td>2.0–32.8</td>
</tr>
<tr>
<td>False NPV, %</td>
<td>9.8–10.3</td>
<td>12.3–53.0</td>
</tr>
<tr>
<td>Contraction duration difference, s</td>
<td>−4.5 to +3.2</td>
<td>+1.7</td>
</tr>
<tr>
<td>Contraction timing difference, s</td>
<td>−11.2 to +4.2</td>
<td>−4.7 to +1.9</td>
</tr>
<tr>
<td>Relative frequency difference with IUPC, %</td>
<td>−1.8 to −1.6</td>
<td>−50.8 to −31.1</td>
</tr>
</tbody>
</table>

All diagnostic parameters of EHG and TOCO were determined in reference to IUPC.

*Depending on the provided data, either number of contractions per 10 or 30 minutes or number of contractions per patient."
was considered as the time between the onset and offset, and the contraction peak as the point in time where the contraction reached the highest measured value. Finally, the IUP estimation of EHG was correlated to the IUPC measured invasively, either directly based on the obtained waveform or from EHG-derived units, such as Montevideo units (MVU) or the area under the curve (AUC). Table 3 summarizes all EHG parameters.

### Diagnostic Parameters

Based on 7 studies, EHG revealed a high sensitivity for contraction detection with values ranging from 86.0% up to 98.0%. In addition, the PPV ranged between 78.7% and 92.0%, thus corresponding to a false-positive contraction ratio of 8.0% to 21.3%. The CCI of EHG ranged from 75.4% up to 88.0%, described in 3 studies. Finally, EHG entailed a false-negative ratio of 9.8% to 10.3% (Table 3).

As EHG has been potentially more prone to artifacts during second stage of labor, 2 studies compared the diagnostic values of EHG in the first and second stages separately. Vlemminx et al showed a decrease in median sensitivity from 91.3% (interquartile range [IQR], 88%–98%) in the first stage to 72.8% (IQR, 61%–87%) in the second stage, P = 0.03. Hayes-Gill et al also found a decrease in sensitivity from 87.8% (95% confidence interval [CI], 84.4%–91.2%) in the first stage to 86.3% (95% CI, 82.0%–90.6%) in the second stage and a decrease in PPV from 81.1% (95% CI, 77.4%–84.8%) in the first stage to 74.1% (95% CI, 66.9%–81.4%) in the second stage (P values not provided).

### Contraction Frequency

In 4 of 6 studies, EHG appeared to overestimate the amount of contractions compared with IUPC by 0.3 up to 0.9 contractions per 10 minute. A 2% underestimation of the contraction frequency was reported in 2 studies by Euliano et al (Table 3).

### Contraction Duration

In 2 studies by Euliano et al, a comparable contraction duration of 55.7 and 77.9 seconds versus 56.4 and 74.7 seconds was reported for EHG and IUPC, respectively. In 2013, Euliano et al reported minor differences in contraction duration as well, with the EHG-derived contractions lasting on average 4.5 seconds less than the reference IUPC (Table 3). Haran et al confirmed these results by the strong correlation coefficient, r, found between the contraction duration of EHG and IUPC (r = 0.90, P < 0.01). Yet, only Jacob et al showed conflicting results about correlation of the contraction duration when considering the filtered EHG signal envelop (r = 0.31; 95% CI, 0.23–0.39).

### Contraction Timing

Timing of the EHG contraction peak has been investigated by 6 studies. In 2 studies, the contraction peak based on IUP-estimated waveforms was 4.5 and 8.5 seconds before IUPC. In Rabotti et al, EHG has been found to precede the IUP by 8.3 to 11.2 seconds, depending on the considered channel. Whereas in 3 other studies, the EHG peak fell slightly after IUPC, that is, 2.0, 2.5, and 4.2 seconds later. When judging the onset and offset of EHG contractions, Euliano et al observed a similar relationship for the detection of the onset (slightly later), whereas offset was nearly identical. These parameters have also been investigated by Haran et al, who reported a strong correlation in the onset, peak, and ending of EHG and IUPC contractions (P < 0.01).

### Waveform Correlation

The IUP waveform estimated by calculation of the EHG energy showed a strong correlation with the IUPC in the study of Rabotti et al (r = 0.73 ± 0.11, P < 0.01) and Rooijakkers et al (r = 0.74 ± 0.13, P < 0.01). Lower correlation figures, r = 0.45 (95% CI, 0.38–0.52) and r = 0.62 (95% CI, 0.56–0.68), have been reported by Jacob et al and Euliano et al, respectively, who used the filtered EHG signal envelop to estimate the IUP waveform. When comparing the energy of EHG to the energy of IUP, a good correlation was found by Maul et al (r = 0.76, P < 0.01) and by Haran et al, who reported correlation figures of r = 0.81, P < 0.01, and r = 0.80, P < 0.01, for AUC and intensity (in mm Hg or μV) of IUPC and EHG waveforms, respectively. These findings were supported by a third study of Euliano et al. In this study, a correlation coefficient of r = 0.80 (P < 0.01) was found between EHG-derived MVU and IUPC-derived MVU. However, in this study, the absolute IUP was shown to be underestimated by EHG by 17.0% ± 20.0% for MVU and 8.0% ± 19.0% for AUC in EHG on average, and an underestimation occurred in 83.0% and 69.0% of the MVU and AUC calculations, respectively. An amplitude mismatch between the IUP estimate and the invasive criterion standard was reflected in the mean square errors obtained by Rabotti et al, Rooijakkers et al, and Skowronski et al.

### Take-Home Message 1

What is the diagnostic value of EHG-based contraction detection relative to IUPC?

Overall, EHG reveals a high sensitivity for...
contraction detection during term labor (Table 3). Electrohysterography detects more contractions in comparison to IUPC, which results in false-positive contractions and a decrease in the PPV. The contraction peak timing in real-time EHG can differ several seconds from IUPC (either before or after). In addition, when using EHG to provide quantitative parameters, patient-dependent EHG amplitudes correlate well with IUP, whereas absolute figures show to underestimate the amplitude.

Question 2: Can EHG Improve External Uterine Monitoring in Comparison to TOCO?

To objectively evaluate the diagnostic value of EHG with TOCO, the IUPC was considered as the criterion standard. As mentioned in paragraph 1, comparison of EHG with IUPC or TOCO was mainly performed by using the IUP-estimated waveform. Our systematic review resulted in 5 studies with simultaneous measurements of IUPC, EHG, and TOCO.54,55,57,60,61 One study compared EHG with TOCO only.47

Diagnostic Parameters

The 86.0% to 94.2% sensitivity of EHG for contraction detection was overall significantly better compared with TOCO by 46.0% to 73.6%, P < 0.01 (Table 3). The mean differences in sensitivity between these 2 external methods ranged from 12.4% up to 44.0%.54,55,57,60,61 Furthermore, Hayes-Gill et al54 showed that this difference in sensitivity between TOCO and EHG was similar in both first and second stages of labor. We found a comparable significant difference in CCI between the external methods of 85.9% to 88.0% with EHG versus 65.1% to 69.0% with TOCO, P < 0.01.54,55,57,60,61 The study of Jezewski et al47 directly compared the external methods and found a CCI of 91.0% for EHG.

The results of other diagnostic parameters (PPV, false PPV, and false NPV) between EHG and TOCO were not consistent throughout the studies. The study of Hayes-Gill et al54 showed contradictory results compared with 3 other studies (Euliano et al,55 Hadar et al,60 and Vlemminx et al57). Electrohysterography performed better than TOCO in these 3 studies, based on a higher PPV and fewer false-positive and false-negative contractions. On the contrary, in the study of Hayes-Gill et al54 EHG reported a lower PPV and more false-positive contractions compared with TOCO.

Contraction Frequency

Throughout the included studies, both EHG and TOCO showed different observations regarding the contraction frequency compared with IUPC (Table 3). A higher frequency was detected in 4 of 6 studies for EHG and 1 of 5 studies for TOCO. A lower contraction frequency was reported in 2 of 6 studies for EHG and 4 of 5 studies for TOCO.50,54,55,57,60,61 Only in Hayes-Gill et al54 EHG detected 0.3 contractions per 10 minutes less than did TOCO.54

Contraction Duration

In a direct comparison of EHG and TOCO, Jezewski et al47 reported that the average contraction duration of EHG was “slightly longer” than that of TOCO. Euliano et al53 also compared the contraction duration of EHG and TOCO in 2 different studies. In 2007, they found no significant differences between 2 uterine monitoring techniques when IUPC was intermittently used.53 The average contraction duration was 68.2 seconds in TOCO versus 76.6 seconds in EHG before IUPC placement, and 74.7 seconds in IUPC versus 77.9 seconds in EHG afterward (see contraction duration difference in Table 3).53

Contrary, when Euliano et al53 compared all 3 methods simultaneously, the average contraction duration was 4.5 seconds shorter in EHG and 1.7 seconds longer using TOCO, with IUPC as reference (Table 3).

Contraction Timing

Five studies evaluated the contraction timing of EHG and TOCO, with the IUPC as reference method. Most of them (4/5) showed that contraction peaks were slightly earlier on the TOCO, varying from 0.6 seconds up to 4.7 seconds before the IUPC peak.54,55,57,60 whereas in only 1 study, the TOCO peaks were 1.9 seconds later.61 The study results about EHG timing were conflicting. In Hayes-Gill et al54 and Hadar et al,60 the EHG peak fell 4.5 and 8.5 seconds before IUPC, respectively, whereas in Vlemminx et al55 and in 2 studies of Euliano et al55,61 these peaks were 2.0, 2.5, and 4.2 seconds after IUPC, respectively. When directly comparing EHG with TOCO, the average timing difference of the contraction peak in these studies ranged between −4 and +4 seconds. Even larger differences were seen by Jezewski et al,47 who reported that EHG contractions preceded the related TOCO contractions with a main time shift of 14 seconds. The group of Euliano et al53 also evaluated the onset and offset of the EHG, TOCO, and IUPC waveforms. The EHG onset fell after IUPC (like the peak), whereas offset was nearly identical in all 3 methods.
Waveform Correlation

Waveform matching was performed by Euliano et al.\textsuperscript{55} The correlation with I UPC waveforms was larger for EHG than TOCO, resulting in a mean correlation coefficient, $r$, of 0.62 for EHG compared with 0.38 for TOCO.\textsuperscript{55} When directly comparing waveforms of the external TOCO with EHG as performed by Jezewski et al,\textsuperscript{37} a very low correlation ($r = 0.16$) between amplitudes and a slightly better correlation for AUC ($r = 0.46$) were detected.\textsuperscript{37}

Take-Home Message 2

Can EHG improve external uterine monitoring in comparison to TOCO?

Electrohysterography reveals a significantly higher sensitivity for uterine contraction detection during term labor compared with TOCO (Table 3). Electrohysterography mainly reports a higher contraction frequency than I UPC, whereas TOCO mostly reports a lower contraction frequency than I UPC. The results of other diagnostic parameters (PPV, false PPV, false NPV, and contraction duration and timing) between EHG and TOCO are not consistent throughout the studies.

Question 3: Is EHG Capable of Improving External Uterine Monitoring in Obese Parturients?

The prevalence of maternal obesity has been increasing worldwide.\textsuperscript{66} A larger subcutaneous thickness deteriorates the mechanical interaction between TOCO and the uterine muscle, which negatively affects TOCO accuracy and can lead to insufficient monitoring.\textsuperscript{57} Therefore, clinical guidelines advise that I UPCs might be beneficial in women where contraction detection by TOCO is difficult because of maternal obesity.\textsuperscript{4,67} Yet, case reports have described severe complications related to I UPC placement.\textsuperscript{8,68} Electrohysterography might be a promising alternative for uterine monitoring in obese parturients. The electrical currents measured by EHG are potentially less suppressed by the adipose tissue layers. This hypothesis has been investigated by 6 studies, which all focused on EHG-based monitoring in obese parturients.\textsuperscript{51,53,55–57}

From a large database of laboring women, Euliano et al\textsuperscript{53} included EHG measurements of 25 women with a body mass index (BMI) of 34 kg/m$^2$ or more. Electrohysterography measurements before and after I UPC placement were evaluated, therefore comparing EHG with TOCO, and EHG with I UPC.\textsuperscript{53} Their EHG method could identify 95.6\% of the TOCO contractions and 97.2\% of the I UPC contractions in these obese women. They calculated the CCI, which was reported to be significantly ($P < 0.01$) better for EHG with I UPC (94.0 ± 6.0) than for EHG with TOCO (77.0 ± 25.0).\textsuperscript{53}

Later, 2 study groups performed prospective simultaneous measurements with all 3 methods, including subgroup analyses in obese women.\textsuperscript{55,57} When evaluating obese women (BMI ≥30 or 35 kg/m$^2$), the sensitivity of EHG (82.0\%–90.2\%) was significantly higher than that of TOCO (45.8\%–65.3\%).\textsuperscript{55,57} The study group of Vlemminx et al\textsuperscript{58} also evaluated the performance of EHG and TOCO in morbidly obese women based on a BMI of greater than 40 kg/m$^2$ during labor. In these subjects, the median sensitivity was 87.2\% with EHG versus 45.0\% with TOCO, $P < 0.01$.\textsuperscript{58} Other test characteristics of EHG in obese and morbidly obese women, such as CCI and PPV, were at least equal to or better than TOCO (Table 3).\textsuperscript{55,57}

In addition, several studies investigated the effect of maternal BMI on the performance of EHG and TOCO. Both previously mentioned study groups showed a negative correlation between maternal obesity parameters and the performance of EHG and TOCO, which was significant only for EHG. In Euliano et al,\textsuperscript{55} the sensitivity of both external methods showed a negative correlation with increasing BMI (EHG $r = −0.23$, $P = 0.07$, and TOCO $r = −0.26$, $P = 0.04$).\textsuperscript{55} The obesity study of Vlemminx et al\textsuperscript{58} showed a similar negative correlation of sensitivity with the obesity parameters BMI before pregnancy (EHG slope $\beta = −0.32$, $r = 0.24$, $P = 0.08$, and TOCO slope $\beta = −1.10$, $r = 0.46$, $P < 0.01$), BMI during labor (EHG slope $\beta = −0.38$, $r = 0.27$, $P = 0.06$, and TOCO slope $\beta = −1.28$, $r = 0.49$, $P < 0.01$), and the abdominal circumference (EHG slope $\beta = −0.16$, $r = 0.24$, $P = 0.09$, and TOCO slope $\beta = −0.59$, $r = 0.50$, $P < 0.01$). Jacot et al\textsuperscript{51} also reported that the agreement of EHG with I UPC was not influenced by maternal BMI. Opposite results were shown in a regression analysis by Cohen and Hayes-Gill.\textsuperscript{56} Uterine contraction recordings with both EHG and TOCO showed no significant deterioration related to BMI for sensitivity, PPV, or false PPV.\textsuperscript{56} When discriminating between different stages of labor, they even reported a significant improvement of EHG sensitivity in the first stage of labor as BMI increased ($P = 0.03$).\textsuperscript{56}
enhanced by EHG as it is much less affected by maternal obesity than TOCO.

**Question 4: What Are the Users’ and Patients’ Experiences on EHG-Based Uterine Monitoring?**

Four studies evaluated the applicability of EHG from the users’ perspectives. Unfortunately, there were no studies evaluating patients’ preferences on uterine monitoring techniques or analyzing the risk on allergic skin reactions due to abdominal electrodes.

In 2011, Reinhard et al were the first to evaluate clinical application of EHG from the perspective of obstetric caregivers. They compared EHG with TOCO tracings during the last 2 hours of the first stage and the whole second stage. Four blinded gynecologists randomly assessed the quality of 30-minute tocogram strips as whether “adequate” or “inadequate.” Overall, a significantly longer portion of EHG strips (average, 138.8 minutes) was judged as adequate compared with TOCO (average, 119.6 minutes), P < 0.01. Electrostrology demonstrated no inadequate tracings, whereas TOCO mainly failed because of inadequate calibration (average, 8.1 minutes) or absent recording (average, 11.2 minutes). A similar relationship was seen when comparing the first and second stages. Furthermore, in Reinhard et al the uterine activity strips were evaluated for assessment as 1 = easy, 2 = intermediate, and 3 = difficult. The obstetric caregivers evaluated monitoring strips significantly “easier” for EHG when compared with TOCO. In the first stage, the average score of was 1.2 for EHG and 2.4 for TOCO, and in the second stage 1.1 for EHG and 2.4 for TOCO.

The portion of interpretable tracings has also been examined in Hadar et al by grading 3 × 30-minute monitoring strips as “interpretable,” “partially-interpretable,” or “uninterpretable.” They found a similar rate of interpretable tracings between physicians for IUPC (94.8%; 95% CI, 83.4%–96.3%) and EHG (87.0%; 95% CI, 80.9%–92.7%) compared with a significantly lower value in TOCO (67.5%; 95% CI, 59.4%–76.8%), P < 0.01. Similar results on interpretability were shown by Euliano et al. In the first stage, 100% of the IUPC and EHG tracings were interpretable, and in the second stage, 96.5% of IUPC and 98.4% of EHG tracings. Conversely, for TOCO, 53.5% in the first stage and 58.7% in the second stage were judged as interpretable (P < 0.01). This superiority of EHG for clinical interpretability was supported by the results of the positive percentage agreement in 3 studies. This diagnostic parameter evaluated the percentage of time that the external devices generated an interpretable tocogram at the same time as IUPC did. This was 97.1% to 100% for EHG and 54.0% to 92.9% for TOCO.

Finally, the interobserver and intraobserver variations of EHG have been examined in 2 studies. The obstetric caregivers in the study of Reinhard et al were tested by repeated measurements, showing that there was no significant intraobserver variability. Yet, their study did show significant differences in observations between the obstetric caregivers regarding the contraction frequency of both external techniques. Euliano et al also evaluated the interobserver variation, which was significantly different for only 1 nurse who had notably higher positive percentage agreement compared with the other 3 observers. Other test parameters showed no significant differences between observers.

**Take-Home Message 4**

*What are the users’ and patients’ experiences on EHG-based uterine monitoring?*

When reviewing EHG from users’ perspectives, obstetric caregivers evaluate EHG tocograms as more interpretable and adequate than TOCO.

**Question 5: Can EHG Provide Parameters for Predicting Labor Outcome, That Is, Vaginal or Cesarean Delivery?**

Besides for contraction detection, EHG has also been investigated in the purpose of predicting the course of term labor. The main goal was to differentiate between inefficient contractions leading to cesarean delivery for arrested labor, in comparison to (spontaneous) vaginal delivery. This research question has been investigated by 2 study groups that focused on different EHG parameters, that is, the spatiotemporal patterns by Euliano et al and the power density spectrum (PDS) by Vasak et al. Both studies provided a specific EHG parameter to discriminate between vaginal and cesarean delivery.

In 2009, the group of Euliano et al investigated the spatiotemporal patterns of uterine electrical activity in normal and arrested labors. They evaluated a 30-minute EHG registration of 12 women with cesarean delivery for term labor arrest, who were matched with 2 women in the same dilation phase (±1 cm of the dystocia) with a normal labor curve and a vaginal delivery. The vertical direction of the center of electrical activity was defined for the first time in this study and analyzed with labor progression. They found a predominantly fundal direction in the patients who delivered vaginally (P < 0.01) and a predominantly downward direction in the patients with cesarean delivery (P = 0.02).

Vasak et al focused on the PDS of contractions in nulliparous during spontaneous onset of labor or in case...
of induction of labor. Previous research has shown that peak frequency of the PDS increases in women at risk of preterm labor, which they attributed to the increased conductivity of the myometrium due to more gap junctions and increased synchronization. They investigated whether this parameter can also be used during term labor to differentiate between normal and protracted labor. In case of spontaneous labor, the peak frequency appeared to be significantly lower in the nulliparous women delivering vaginally (without oxytocin 0.49 Hz, with oxytocin 0.51 Hz) compared with women delivering with cesarean (0.55 Hz). Moreover, the mean peak frequency of the PDS increased after the onset of administration of oxytocin. On the contrary, in case of labor induction, they found no differences in the EHG PDS between women who delivered vaginally (with or without oxytocin) and women with a cesarean delivery.

Take-Home Message 5
Can EHG provide parameters for predicting labor outcome, that is, vaginal or cesarean?
Two EHG parameters are identified to predict vaginal birth such as an electrical activity pattern with more fundal direction and a lower peak frequency in case of spontaneous labor. However, the methods to estimate these parameters are not yet suitable for daily practice.

DISCUSSION

Electrohysterography is a noninvasive technique for real-time uterine monitoring during term labor, which could potentially overcome the drawbacks of current monitoring techniques (ie, IUPC and TOCO). In addition, EHG could provide additional information on the uterine activity pattern by measuring the root cause of uterine contractions (ie, uterine electrical activity). As real-time EHG technologies have become available for use on the labor ward, we performed a systematic review on the diagnostic value, advantages, and limitations of EHG during term labor.

Based on the results of this systematic review, EHG revealed a high sensitivity for contraction detection during term labor, with reported values between 86.0% and 98.0%. Relative to TOCO, improvement of external uterine monitoring accuracy has been reported by EHG of both nonobese and obese women. Electrohysterography was also less affected by maternal obesity than TOCO. When using EHG as real-time method, physicians do need to be aware that the contraction peak timing in EHG might differ several seconds from IUPC (either before or after). In addition, EHG detected more contractions compared with both conventional techniques, which resulted in false-positive contractions and a decrease in the PPV. Patient-dependent EHG amplitudes correlated well with IUP to provide quantitative parameters, whereas absolute figures showed to underestimate the amplitude. Furthermore, when reviewing EHG from users' perspectives, obstetric caregivers evaluated EHG tocograms as more interpretable and adequate than TOCO. Unfortunately, patients' experiences were not reported. Finally, our review identified 2 EHG parameters to predict vaginal birth such as an electrical activity pattern with more fundal direction and a lower peak frequency in case of spontaneous labor.

Electrohysterography is evaluated in comparison to TOCO because of its widespread application and to IUPC because this is the current criterion standard for uterine monitoring. As shown by this review, EHG can provide an accurate tocogram of continuous good quality by measuring these underlying biopotentials. Yet, a direct comparison between IUP and EHG is difficult. The different nature of each of the uterine monitoring techniques here discussed (IUPC, TOCO, and EHG) should be carefully taken into consideration.

Electrohysterography reflects the sum of the electrical activity in the myometrial smooth muscle cells that evoke increasing pressure of the amniotic fluid inside the uterine cavity. Absolute EHG traces depend on several factors such as electrode location at the abdomen, distance to the myometrium, skin impedance, and other patient-dependent variables. Reduction of the impedance by skin preparation is essential for proper data acquisition; however, this could cause skin irritation. In addition, most of the current EHG systems do not provide wireless connectivity and cannot be applied under wet conditions. Therefore, EHG can accurately monitor the uterine activity pattern from the maternal abdomen, but absolute figures need to be interpreted with caution, and there are still some minor practical limitations of EHG.

Intrauterine pressure catheter, which is still considered as the criterion standard, can accurately measure pressure variation of the amniotic fluid in mm Hg induced by contraction of the myometrium. Intrauterine pressure catheter thus measures an indirect effect (increase IUP) instead of the origin (electrical activity) of uterine contractions. In addition, the accuracy of IUPC measurements can be influenced by maternal position, maternal movements, amniotic fluid weight, and/or atmospheric pressure. For example, insertion of 2 identical IUPCs in 1 uterine cavity (either tied together or independently) revealed differences in the pressure peak (up to 30–40 mm Hg) between the 2 catheters in both groups. Margono et al also revealed pressure differences.
between a catheter in the upper and the lower parts of the uterine cavity. Furthermore, the invasive IUPC catheters are related to rare but severe complications and are not free from technical issues such as blockage of the catheter or an uninterpretable signal (up to 10% of the cases). In addition, women are less mobile with an IUPC as it can fall out when they walk around. Finally, a large randomized controlled trial and Cochrane review showed no effect on labor outcome by applying IUPC compared with TOCO. Altogether, IUPC can accurately monitor uterine contractions but has some shortcomings related to its invasive character and effect on labor outcome.

External tocodynamometer is widely accepted for uterine monitoring during term labor. This technique consists of an external strain gauge transducer positioned at the maternal abdomen with an elastic belt. External tocodynamometer provides continuous information on the contraction frequency by measuring shape changes of the maternal abdominal wall noninvasively. Wireless connections and waterproof models are available with TOCO. However, TOCO has a moderate sensitivity (46.0%–73.6%) for uterine contraction detection, and contraction intensity is not assessed as the contraction curve depends on the transducer position and interface with the uterine muscle. A direct comparison of TOCO to IUPC showed a poor correlation coefficient \((r)\) for contraction amplitude \((r = 0.26)\) and duration \((r = 0.27)\), but a good correlation with the contraction frequency \((r = 0.75)\). In addition, its accuracy is negatively influenced by maternal obesity because of larger distance between the uterus and abdominal transducer. External tocodynamometer requires a tight, uncomfortable belt around the abdomen and needs frequent position modifications as maternal movements affect its position at the abdomen. Quality assessment of TOCO monitoring strips reveals a low quality throughout labor. Only 2% of the TOCO traces during the last 2 hours of the first stage were of good quality, and 30% during the second stage. Thus, TOCO can safely provide information on the contraction frequency; however, it has a low accuracy, and it takes some effort to provide a tocogram of continuous good quality.

Electrohysterography has several advantages compared with the currently used uterine monitoring techniques. Electrohysterography is highly sensitive to uterine contraction detection without being invasive. In Table 4, we provide an overview of the antepartum and intrapartum indications for EHG monitoring. If TOCO does not work adequately, physicians can safely switch to EHG as an alternative monitoring technique instead of the invasive IUPC. Electrohysterography does not require ruptured membranes or a certain dilation, and there is no risk of placental damage as with IUPC. Electrohysterography might be helpful when an obstetric caregiver cannot safely rupture the membranes (eg, when the fetal caput is not engaged) but does need to improve labor surveillance because of inadequate TOCO monitoring (eg, during trial of labor after cesarean delivery or in case of suspected fetal distress). External uterine monitoring in obese women can also be improved by EHG. Maternal obesity is one of the most common risk factors during pregnancy, which is related to numerous pregnancy complications such as hypertension, preeclampsia, gestational diabetes, and macrosomia. In addition, obese women have an increased risk of labor induction and an emergency cesarean delivery. Given these additional risks, obese women particularly require close labor surveillance. External monitoring can be significantly improved by EHG relative to TOCO as the electrical signals measured by EHG are significantly less hampered by abdominal fat tissue than the abdominal wall changes measured by TOCO. In addition, because of the adhesive properties, EHG can provide a more continuous tocogram of good quality, which has been confirmed by users’ evaluations. Overall, EHG can enhance uterine monitoring because of its noninvasiveness, adhesive properties, and reduced obesity sensitiveness.

Electrohysterography systems measure, on average, more contractions compared with IUPC (from 0.3 to 0.9 extra contractions per 10 minutes). These extra contractions may be related to artifacts, as well as to the electrophysiological origin of contractions. Artifacts such as the maternal ECG (>1 Hz), maternal breathing movements (<0.3 Hz), and pressure/stretch at the electrodes are a well-known challenge for electrophysiological measurements. Different approaches ranging from simple band-pass filtering to more dedicated algorithms have been proposed to mitigate the effect of these artifacts in biopotential measurements. Yet, partial removal may result in false-positive contractions. However, based on the complex physiology of uterine contractility, the “extra” contractions might be actual local activity patterns, which are not globally transferred throughout the whole myometrium. This results in EHG bursts without increase in the IUP.
among studies. In addition, each EHG-measurement configuration, and skin preparation varied significantly. The inter-electrodes distance, use of monopolar or bipolar recordings, however the number and location of electrodes, abdominal electrodes for uterine electrophysiological use general purpose devices. Each design incorporated electrode configuration and used equipment. Some participants are applicable for our research questions.

The main strength of our systematic review is providing an extended overview of the EHG test characteristics for uterine monitoring during term labor that could be useful for optimal interpretation of EHG traces in clinics. The summarizing table provides physicians a clear overview. In addition, general quality of the included diagnostic studies is adequate, as most studies compare EHG to the criterion standard IUPC and the study participants are applicable for our research questions.

Among the included studies, the technical features broadly differed in terms of signal analysis methods, electrode configuration and used equipment. Some applied dedicated commercial EHG systems while others used general purpose devices. Each design incorporated abdominal electrodes for uterine electrophysiological recordings, however number and location of electrodes, inter-electrodes distance, use of monopolar or bipolar configuration, and skin preparation varied significantly among studies. In addition, each EHG-measurement device was equipped with signal-processing software to enhance data quality. Most studies applied a bandpass filter, yet the filter settings were slightly varying per study (Table 1). Thus, physicians should be aware of these technical variances when reading this review.

Dissimilarities between studies were also seen regarding the criteria for contraction detection, probably due to the limited amount of literature on defining uterine contraction curves. Moreover, evaluation of contraction waveform was either computer- or expert-based, which both have pros and cons. Computer-based evaluations are most objective and based on strict predefined definitions, yet do not take into consideration that tocograms obtained from different methods (IUPC, TOCO and EHG) have a characteristic configuration. Whereas expert-based evaluations are less subjective than computer-based analysis, yet they do represent daily practice. Furthermore, we assume that obstetric caregivers are better able to recognize false positive contractions due to artifacts than computerized analysis. While all these technical details were meticulously reported, the impact of the technical-methodological discrepancies of the included studies has not been critically analyzed as it was beyond the scope of the review. However, this might have limited the depth of our comparative analysis.

Uterine monitoring during term labor is expected to be among the first clinical application of EHG-based technologies. Further research is necessary to assess the clinical impact of using the EHG-based cardiotocogram. Improvement of the tocogram by EHG enables better evaluation of FHR patterns and better adjustments of the oxytocin dosage, which could potentially result in improved perinatal outcome. In addition, clinical implementation, cost-effectiveness, and patients' preferences need to be evaluated as well. As we mentioned in the introduction, the costs of EHG are higher than TOCO because of the disposable sensors. The EHG system (PUREtrace module and Graphium patch; Nemo Healthcare, Veldhoven, the Netherlands) used by Vlemmix et al costs approximately US $62 for 1 disposable electrode patch, which is comparable to approximately US $57 for 1 disposable IUPC (Koala; Clinical Innovations, Murray, Utah). These additional costs of EHG should be balanced to the potential improvement of labor outcome and labor management and thereby whether EHG can be cost-effective.

Other EHG applications are currently being considered aiming at improving pregnancy and labor outcome. Our paragraph on predicting term labor outcome already revealed 2 specific EHG parameters (a more fundal direction of the electrical activity pattern and a lower peak frequency in case of spontaneous labor), which can help obstetrician-based decision making related to labor induction and management. Other promising applications of EHG are to differentiate between false and true labor and to evaluate the effect of medical treatments such as tocolytic drugs and labor analgesia. For example, in the study of Ye et al on epidural analgesia, EHG activity was initially suppressed after epidural and recovered as labor progressed. These EHG-based evaluations might be useful to call a halt to the increasing cesarean delivery rate worldwide, especially because of failed induction, nonprogressive labor, and fetal distress.

Further, EHG may also add to the diagnosis of special cases such as uterine rupture or placental abruption. These are all promising applications, yet are currently not available for daily labor care.

Based on this review, EHG offers obstetric caregivers a noninvasive and accurate method to monitor uterine contractions throughout labor. Electrohysterography should be balanced against the advantages and disadvantages of the currently available IUPC and TOCO, that is, the accuracy and invasiveness of IUPC versus the inaccuracy...
and safety of TOCO. In addition, waterproof and wireless systems are needed, and patients' preferences should be evaluated. In conclusion, if the widely used TOCO monitor is inadequate, EHG should be available on the labor ward to safely improve intrapartum monitoring instead of the invasive IUPC.

REFERENCES


