35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

Low-complexity intrauterine pressure monitoring by Teager energy estimation

M.J. Rooijakkers, C. Rabotti, S.G. Oei, R.M. Aarts, and M. Mischi

Abstract— **Monitoring the progression of maternal uterine activity provides important prognostic information during pregnancy and parturition. Currently used methods, however, are unsuitable for long-term observation of uterine activity. The abdominally measured electrohysterogram (EHG) provides a non-invasive alternative to the existing methods for long-term ambulatory uterine contraction monitoring. A new EHG signal analysis method for intrauterine pressure (IUP) estimation based on the Teager energy estimate is proposed. The new method is compared to existing methods from the literature in terms of estimation accuracy and computational complexity. An accurate IUP estimate, with a complexity up to 40 times lower than that of algorithms from the literature is obtained. Therefore, the proposed method offers a valuable new option for long-term uterine monitoring.**

I. INTRODUCTION

Preterm birth is associated with over 75% of perinatal mortality and more than 50% of perinatal and long-term morbidity [1]. Early prediction of preterm delivery by accurate monitoring of patients at risk is crucial for prevention of preterm birth. Tracking the progression of maternal uterine activity during pregnancy, by determining frequency, duration, and amplitude of the uterine contractions, can give insight in the time to delivery [2]. Correct calculation of these variables requires accurate measurement of the intrauterine pressure (IUP).

In clinical practice, uterine activity is generally monitored by direct or indirect measurement of the IUP. Currently, the method that is most widely used to monitor the uterus during pregnancy and delivery is external tocography. It uses a tocodynamometer, which consists of a strain gauge transducer, placed on the abdominal surface to indirectly estimate the IUP. External tocography can be used throughout pregnancy, as it is non-invasive. However, deriving the IUP estimate from an indirect mechanical measure makes it very susceptible to movement artifacts and unreliable on obese patients [3], [4]. This can results in a low sensitivity and affects the accuracy of the estimated contraction amplitude and duration. During delivery, an internal uterine pressure catheter (IUPC) can be used to obtain a quantitative direct measurement of the IUP. However, the use of an IUPC requires rupturing of the amniotic membranes and increases the risk of infections or damage to the fetus; it is therefore employed during parturition only [5].

This work was supported by the Dutch technology foundation STW

M.J. Rooijakkers, C. Rabotti, R.M. Aarts, and M. Mischi are with the Faculty of Electrical Engineering, University of Technology Eindhoven, 5612 AZ, Eindhoven, The Netherlands m.j.rooijakkers@tue.nl

S.G. Oei is with the Máxima Medical Center, 5504 DB, Veldhoven, The Netherlands

Measurement of the electrohysterogram (EHG), which is the bioelectrical signal resulting from propagation of action potentials in the myometrium, *i.e.* the uterine muscle, gives an indication of uterine activity. The IUP increase associated with each contraction can therefore be estimated, providing essential information on the uterine activity [6], [7]. During pregnancy, the electrical resistance between myometrial cells is relatively high, while at term, low-resistance paths form, leading to the occurrence of effective contractions [8]. The EHG can, therefore, be used to estimate the IUP as well as to give an indication of the time to delivery. Because this technique is non-invasive, due to the use of abdominal electrodes, it is suitable for long-term uterine observation throughout pregnancy.

Various methods have previously been proposed for EHG analysis, comprising statistical approaches [9], filtering techniques [10], fast Fourier transform (FFT) [11], the wavelet transform [3]. However, only recent studies focused on EHG analysis as an alternative method for quantitative IUP estimation [12], [13], [14]. An estimated contraction pattern obtained by taking the root mean square (RMS) value of the EHG was compared to the simultaneously recorded external tocogram in [12]. The estimated contraction pattern showed a high correlation with the externally measured tocogram, and was hence shown to be a reliable estimator for the contraction frequency. A spectrogram-based technique to obtain an IUP estimate was employed by [14]. Results showed a high correlation of the IUP estimate with the simultaneously measured internal IUP. Compared to the RMS-based algorithm in [12], the spectrogram-based algorithm proposed by [14] shows a clear improvement in the correlation with the IUP. The complexity of the method has, however, increased accordingly, reducing its potential for long-term ambulatory uterine activity monitoring.

A new algorithm based on the Teager energy (TE) operator is proposed as an alternative method for accurate long-term IUP estimation [15], [16]. The TE operator is used to model the power of the mechanical process of the contraction from the electrical energy in the EHG signal, with a reduced computational complexity. The proposed algorithm is validated based both on the correlation of the UIP estimate with the internally measured IUP as well as the root mean square error (RMSE), and compared to algorithms from the literature. To this end, a dataset of abdominal EHG measurements with simultaneous internal IUP recordings was used. Additionally, the analyzed algorithms are compared based on computational complexity.

II. METHODOLOGY

The TE operator is introduced as an estimator of energy and is proposed as part of a simple algorithm for IUP estimation. The TE operator is used because of its ability to determine the frequency-weighed energy of the EHG signal, which resembles the physiological process leading to contraction of the myometrium. Additionally, two IUP estimation methods from the literature are described for comparison.

A. Teager energy

The TE operator Φ represents a local property of the signal depending only on the signal and its first two time derivatives, as introduced in [15], [16]. In the continuous time domain, the application of the operator Φ to an input signal $x(t)$ is defined as

$$\Phi\left[x(t)\right] = \left(\frac{dx(t)}{dt}\right)^2 - x(t)\frac{d^2x(t)}{dt^2} \quad (1)$$

In the discrete time domain, the TE operator becomes

$$\Phi\left[x(n)\right] = x(n)^2 - x(n+1)x(n-1), \quad (2)$$

where, n indicates the index of the signal sample in x. As can be seen in (2), $\Phi\left[x(n)\right]$ only spans three consecutive samples of x to calculate the instantaneous energy at time n, giving an excellent time resolution. TE is also robust to white noise and is very suitable for detection of transients in noisy signals [17], [18]. However, the TE operator is not linear when superimposing two or more signals, which results in an underestimation of the total signal energy [15]. Therefore, in order to calculate an exact energy using the TE operator, the various frequency components of the analyzed signals need to be separated before energy calculation. To this end, a multiband solution for energy tracking over a wideband signal is introduced in [19], which requires band-pass (BP) filtering of multiple sub-bands and calculating the TE in each sub-band. Because the energy of the EHG is concentrated in a limited frequency band, the use of a single TE operator seems a suitable choice.

B. TE-based IUP estimation

First, the input signal $x(n)$ is filtered using a BP filter with 3dB low and high cutoff at $f_{\min} = 0.3$ Hz and $f_{\max} = 0.8$ Hz, respectively, in line with [14]. This creates a filtered EHG signal $x_f(n)$, which is processed using the TE operator in (2) to yield the instantaneous energy of the EHG signal. Finally, the TE IUP estimate (IUP_{TE}) is calculated using the moving average of $\Phi\left[x(n)\right]$, as defined by

$$\mathrm{IUP}_{TE}\left[x_f(n)\right] = \frac{1}{M}\sum_{m=-M/2}^{+M/2}\Phi\left[x_f(m+n)\right], \quad (3)$$

with, $M \equiv 30$ s.

C. Spectrogram-based IUP estimation

In [14], the spectrogram $\rho(t,f)$ is first calculated using a FFT with a Hamming window $w(t)$ of length 70 s as defined by

$$\rho(t,f) = \left|\int_{-\inf}^{+\inf} x(\tau)w^*(\tau-t)e^{-j2\pi f\tau}d\tau\right|^2, \quad (4)$$

where $(\cdot)^*$ is the conjugate operator. The unnormalized first statistical moment $\Psi(t)$ is calculated by scaling $\rho(t,f)$ for each frequency interval in the IUP frequency range $[f_{\min},\ f_{\max}]$ by its mean frequency f, as described by

$$\Psi\left(t\right) = \int_{f_{\min}}^{f_{\max}} f\cdot\rho\left(t,f\right)df. \quad (5)$$

Therefore, $\Psi\left(t\right)$ uses the simultaneous increase of both the frequency- and amplitude-related features of the EHG signal to determine the IUP wave estimate.

In [14] a second-order model is used to reduce the influence of muscle fatigue and the physiology underlying the relation between electrical activity and contractility. Use of the model only results in a minor improvement; therefore, $\Psi\left(t\right)$ is used as the spectrogram-based IUP estimate IUP_S.

D. RMS-based IUP estimation

In the RMS-based IUP estimation algorithm from [12], the EHG is first BP filtered between 0.05 Hz and 5 Hz, resulting in the filtered signal $x_f(n)$. Next, the RMS IUP estimate (IUP_R) is calculated by

$$\mathrm{IUP}_R[x_f(n)] = \sqrt{\frac{1}{M}\sum_{m=-M/2}^{+M/2}\left\{x_f(m+n)w(m)\right\}^2}, \quad (6)$$

where, $M \equiv 60$ s is the total number of samples in the Hanning window $w(m)$, which used to reduce edge effects.

III. VALIDATION

A. Measurements

A set of nine measurements on women during labor was performed. All women signed an informed consent. Recordings were made using two active unipolar electrodes, horizontally spaced by 12 cm, as well as a ground and reference electrode, placed on the abdomen as shown in Fig. 1 [14]. All electrodes were contact Ag-AgCl electrodes. They were placed on the abdomen after skin preparation with abrasive paste to reduce skin impedance. The IUP was measured simultaneously using an IUPC, which was applied due to medical prescription. The IUP and the EHG were both recorded at 1 kHz using a M-PAQ (Maastricht Instruments B.V., The Netherlands). The total length of the measurements is approx. 10 hours and 26 min with measurements for each subject ranging from 22 to 90 minutes.

Both the EHG and IUP signal were preprocessed before use in the comparative analysis. The IUP signal, which is adopted as the golden standard reference signal, was cleaned to minimize spikes caused by movement artifacts using a

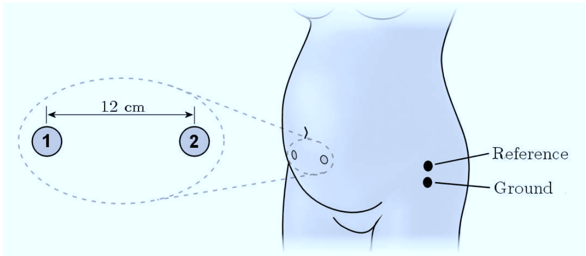

Fig. 1. Electrode configuration used for IUP measurements.

non-causal centered median filter with a length of 5 s [12]. A bipolar EHG signal was extracted from the two active unipolar electrodes, after which both EHG and IUPC signals were downsampled to 10 Hz using an anti-aliasing filter at 4 Hz. This is possible because all EHG signals are present in the 0.3 Hz to 3.0 Hz frequency band [11], [14], [20], [21].

B. Quality measures

Validation of the various IUP estimation algorithms was performed by comparing both the accuracy of the estimated IUP as well as their complexity. The correlation coefficient r and RMSE are used as quality measures for the accuracy of the various algorithms in estimating the IUP. Here, r is defined as

$$r = \frac{\sum_{i=1}^{N}(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{N}(x_i - \overline{x})^2 \sum_{i=1}^{N}(y_i - \overline{y})^2}}, \quad (7)$$

with, x being the IUP estimate, y the IUPC signal, $\overline{x}$ and $\overline{y}$ their means, respectively, and N the total number of samples in the signal. The correlation coefficient r is in the range $-1 \leq r \leq 1$, where a higher value defines a better match between the signals. Before calculation of the RMSE and r for the described methods, the basal tones of all IUP signals were removed using the method described in [12] and their amplitudes were scaled to best match the IUPC signals.

The average number of multiplications per sample (MPS) is used as a measure of computational complexity. All operations with a complexity higher than a multiplication, *e.g.* a division or square root, can be represented by multiple multiplications. Both operations have a complexity in the order of $O[n]$, where n is the accuracy of a value in number of bits. Assuming an accuracy of 16 bits for both numerator and denominator, a division and square root are substituted by 9 and 17 multiplications, respectively [22]. All simple operations, *e.g.* addition, subtraction or bit-shift, are left out of consideration.

The computational complexity of the FFT-based spectrogram can also be expressed as the number of multiplications used. The FFT can be implemented based on a butterfly principle, with a complexity of $O[N\log_2(N)]$ [23], where N is the length of the FFT window and a power of 2. Optimizations have led to a number of multiplications in the order of $O[(N/2)\log_2(N)]$ [24], [25], with as little as 3586 multiplications for $N = 1024$ [26].

IV. Results

Fig. 2 shows a comparison of the three IUP estimates discribed in this paper with the reference IUPC signal.

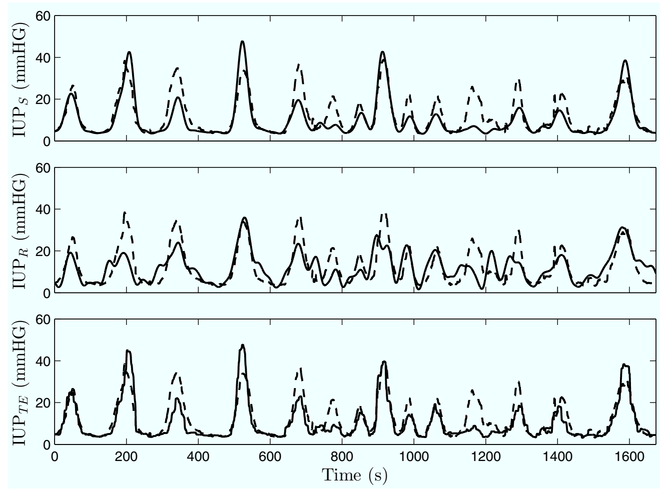

Fig. 2. From top to bottom, the IUP estimated using the spectrogram-, RMS-, and TE-based methods (solid) is compared to the IUPC signal (dashed).

Table I shows the total number of operations needed for each of the three described algorithms when operating on an EHG signal sampled at 10 Hz. The four columns from left to right give the number of square roots, divisions, multiplications, and summations, respectively.

TABLE I

AMOUNT OF COMPUTATIONS PER CLASS NEEDED TO PERFORM THE VARIOUS OPERATIONS FOR EACH OF THE ALGORITHMS

		$\sqrt{x}$	x/y	$x \cdot y$	$x \pm y$
Spec. [14]	FFT	0	0	3586	13503
	Square	0	0	1	0
	Freq. comp.	0	0	28	27
	Total	**0**	**0**	**4625**	**14129**
RMS [12]	HP filter $[0.05 - \cdot]$	0	0	657	656
	Hanning window	0	0	300	599
	RMS	1	1	1	2
	Total	**1**	**1**	**958**	**1257**
TE	BP filter $[0.3 - 0.8]$	0	0	107	106
	TE operator	0	0	2	1
	Mean	0	1	0	2
	Total	**0**	**1**	**109**	**109**

Table II shows the average of both the correlation coefficient r and RMSE for all patients including inter-patient variation, for each of the described methods.

TABLE II

PERFORMANCE COMPARISON OF IUP ESTIMATION ALGORITHMS

	$r(p < 0.01)$	RMSE (mmHG)	MPS
Spectrogram [14]	0.69 ± 0.19	9.93 ± 4.67	4625
RMS [12]	0.42 ± 0.28	12.72 ± 5.26	984
Teager energy	0.68 ± 0.20	10.21 ± 5.23	118

V. Discussion and conclusion

In this paper we propose a non-invasive method to estimate the IUP by modeling it as the electrical energy in the EHG signals calculated using the TE operator. The method was tested on a set of measurements from nine women in labor. Each measurement contains two monopolar EHG signals and a simultaneously measured IUPC signal, both sampled at 1 kHz. The TE algorithm was compared with two alternative IUP estimation methods proposed in the literature in terms of both IUP estimation quality and computational complexity. These alternative methods are the spectrogram-based technique proposed in [14] and the RMS-based method described in [12].

The spectrogram-based method reflects the fundamental physiologic phenomena underlying the generation of the EHG signal, and takes the influence of the signal frequency content on the contractile strength into account. Therefore, the estimation accuracy of the IUP is high with a mean r of 0.69 and a RMSE of 9.93 mmHG. The computational complexity, however, is relatively high with 4625 MPS, limiting its use in long-term mobile uterine monitoring. The RMS analysis, in comparison, is relatively simple, with 1257 MPS, and suitable for real-time applications. However, the EHG signal envelop shows a much lower correlation with the reference IUP and is, therefore, a much less reliable IUP estimator. The proposed TE method, similarly to the spectrogram, takes the influence of the signal frequency content into account. This results in the TE-based IUP estimation giving correlation results comparable to the spectrogram-based method. Additionally, a reduction in computational complexity by a factor 40 is obtained compared to the spectrogram, making the TE method very suitable for real-time applications.

IUP estimation by the proposed algorithm can still be improved using a physiological model or multiband filtering prior to TE calculation. Improvements might however not be significant compared to the corresponding increase in computational complexity, seeing that there is only a marginal difference in r between the TE- and spectrogram-based methods. The complexity of each of the three described methods can also be reduced significantly, by choosing optimal sampling frequencies and window shapes and sizes. Changing the window shape of the sliding FFT alone can already reduce the order of complexity to $O[N]$ [25], [27].

In the future, we will therefore focus on further reduction of the computational complexity of the proposed algorithm, as well as the alternatives, while improving the IUP estimation quality.

References

[1] R. L. Goldberg and E. M. McClure, *Preterm Birth: Prevention and Management*. John Wiley & Sons, Jan. 2010, ch. 4, pp. 22 – 38.

[2] D. Bentley, *et al.*, "Relationship of uterine contractility to preterm labor." *Obstet Gynecol*, vol. 76, no. 1 Suppl., pp. 36S – 38S, Jul. 1990.

[3] H. Eswaran, J. D. Wilson, P. Murphy, H. Preissl, and C. L. Lowery, "Application of wavelet transform to uterine electromyographic signals recorded using abdominal surface electrodes," *J. Matern-Fetal Neo. M.*, vol. 11, no. 3, pp. 158 – 166, 2002.

[4] T. Y. Euliano, M. T. Nguyen, D. Marossero, and R. K. Edwards, "Monitoring contractions in obese parturients: Electrohysterography compared with traditional monitoring," *Obstet. Gynecol.*, vol. 109, no. 5, pp. 1136 – 1140, May 2007.

[5] R. E. Garfield, *et al.*, "Uterine electromyography and light-induced fluorescence in the management of term and preterm labor," *J Soc Gynecol Investig*, vol. 9, no. 5, pp. 265 – 275, Sep. 2002.

[6] R. E. Garfield and W. L. Maner, "Physiology and electrical activity of uterine contractions," *Seminars in Cell & Developmental Biology*, vol. 18, no. 3, pp. 289 – 295, Jun. 2007.

[7] T. Y. Euliano, *et al.*, "Monitoring uterine activity during labor: a comparison of 3 methods," *American Journal of Obstetrics and Gynecology*, vol. 208, no. 1, pp. 66.e1 – 66.e6, Jan. 2013.

[8] R. Garfield, *et al.*, "Control and assessment of the uterus and cervix during pregnancy and labour," *Human Reproduction Update*, vol. 4, no. 5, pp. 673 – 695, 1998.

[9] K. Horoba, S. Graczyk, J. Jezewski, A. Gacek, and J. Wrobel, "Statistical approach to analysis of electrohysterographic signal," in *EMBC*, vol. 2, Oct. 1999, p. 887.

[10] K. Horoba, J. Jezewski, J. Wrobel, and S. Graczyk, "Algorithm for detection of uterine contractions from electrohysterogram," in *EMBC*, vol. 3, Oct. 2001, pp. 2161 – 2164.

[11] C. Buhimschi, M. B. Boyle, and R. E. Garfield, "Electrical activity of the human uterus during pregnancy as recorded from the abdominal surface," *Obstet. Gynecol.*, vol. 90, pp. 102 – 111, Jul. 1997.

[12] J. Jezewski, K. Horoba, A. Matonia, and J. Wrobel, "Quantitative analysis of contraction patterns in electrical activity signal of pregnant uterus as an alternative to mechanical approach," *Phys. Meas.*, vol. 26, no. 5, pp. 753 – 767, Jul. 2005.

[13] M. Skowronski, J. Harris, D. Marossero, R. Edwards, and T. Euliano, "Prediction of intrauterine pressure from electrohysterography using optimal linear filtering," *IEEE Trans. Biomed. Eng.*, vol. 53, no. 10, pp. 1983 – 1989, Oct. 2006.

[14] C. Rabotti, M. Mischi, J. O. E. H. van Laar, G. S. Oei, and J. W. M. Bergmans, "Estimation of internal uterine pressure by joint amplitude and frequency analysis of electrohysterographic signals," *Phys. Meas.*, vol. 29, no. 7, pp. 829 – 841, Jul. 2008.

[15] J. Kaiser, "On a simple algorithm to calculate the 'energy' of a signal," in *ICASSP-90.*, vol. 1, Apr. 1990, pp. 381 – 384.

[16] ——, "Some useful properties of Teager's energy operators," in *ICASSP-93.*, vol. 3, Apr. 1993, pp. 149 – 152.

[17] R. Dunn, T. Quatieri, and J. Kaiser, "Detection of transient signals using the energy operator," in *ICASSP-93.*, vol. 3, Apr. 1993, pp. 145 – 148.

[18] D. Sherman, *et al.*, "Detecting EEG bursts after hypoxic-ischemic injury using energy operators," in *EMBC*, vol. 3, Oct. 1997, pp. 1188 – 1190.

[19] G. Evangelopoulos and P. Maragos, "Multiband modulation energy tracking for noisy speech detection," *IEEE Audio, Speech, Language Process.*, vol. 14, no. 6, pp. 2024 – 2038, Nov. 2006.

[20] W. L. Maner, R. E. Garfield, H. Maul, G. Olson, and G. Saade, "Predicting term and preterm delivery with transabdominal uterine electromyography," *Obstet. Gynecol.*, vol. 101, no. 6, pp. 1254 – 1260, Jun. 2003.

[21] H. Leman, C. Marque, and J. Gondry, "Use of the electrohysterogram signal for characterization of contractions during pregnancy," *IEEE Trans. Biomed. Eng.*, vol. 46, no. 10, pp. 1222 – 1229, Oct. 1999.

[22] A. Robison, "N-bit unsigned division via n-bit multiply-add," in *17th IEEE Symposium on Computer Arithmetic*, Jun. 2005, pp. 131 – 139.

[23] L. Rabiner and R. Schafer, "Recursive and nonrecursive realizations of digital filters designed by frequency sampling techniques," *IEEE Trans. Audio Electroacoust.*, vol. 19, no. 3, pp. 200 – 207, Sep. 1971.

[24] L. R. Rabiner and B. Gold, *Theory and application of digital signal processing*. Englewood Cliffs, N.J.: Prentice-Hall, 1975.

[25] B. Farhang-Boroujeny and Y. Lim, "A comment on the computational complexity of sliding FFT," *IEEE Trans. Circuits Syst. II, Analog Digit. Signal Process.*, vol. 39, no. 12, pp. 875 – 876, Dec. 1992.

[26] M. E. Vetterli and H. J. Nussbaumer, "Simple FFT and DCT algorithms with reduced number of operations," *Signal Processing*, vol. 6, no. 4, pp. 267 – 278, Aug. 1984.

[27] M. T. Signes, J. M. Garca, and H. Mora, "Improvement of the discrete cosine transform calculation by means of a recursive method," *Math. Comput. Model.*, vol. 50, no. 5-6, pp. 750 – 764, Sep. 2009.