Proceedings of the International Conference of
Bioelectromagnetism, Electrical Bioimpedance, and Electrical Impedance Tomography
June 28 – July 1, 2022 / Kyung Hee University, Seoul, Korea

High resolution EIT based heart rate detection using Synchrosqueezing

Henryk Richter[1], Lisa Krukewitt[2], Fabian Müller-Graf[2], Amelie Zitzmann[2], Jonas Merz[2], Stephan Böhm[2], Volker Kühn[1]

[1]Institute of Communications Engineering, University of Rostock, Germany
[2]Department of Anesthesiology and Intensive Care Medicine, University Medical Center Rostock, Rostock, Germany

Correspondence: Henryk Richter, e-mail: `henryk.richter@uni-rostock.de`

Abstract: A major challenge in EIT based monitoring of cardiovascular activity is the relatively low signal-to-noise ratio of perfusion related signals. This work is aiming at high resolution instantaneous heart rate estimation in frequency domain to aid in de-noising and beat-by-beat analysis. Our approach is based on the Fourier domain Synchrosqueezing transform. We evaluate the performance of our algorithm by synchronous in vivo measurements of EIT and ECG.

Keywords: EIT; Synchrosqueezing; HR detection

1 Introduction

EIT has been studied extensively for medical applications in the area of ventilation monitoring and, more recently, monitoring of the perfusion process. One major challenge for perfusion monitoring is the dominance of the ventilation signal in EIT. Several algorithms have been proposed to separate ventilation and perfusion signal parts (Deibele et al. 2008; Jang et al. 2020; Richter et al. 2021) which also have the benefit of relaxing the heart rate estimation task. Typically, perfusion related signals are measured with significantly lower amplitude in comparison to the ventilatory signal, such that the noise influence becomes a major concern. A common approach in noise reduction of cardiac signals is the averaging over multiple cardiac cycles using the R-Peaks of a parallel measured ECG as a trigger (Vonk Noordegraaf et al. 2000). From the signal processing perspective, the cardiac signal is an instationary process where the heart rate varies on a beat by beat basis. The variational property of the heart rate along with significant measurement noise poses a challenge to accurate estimates of the instantaneous heart rate by classic methods like STFT or parametric approaches like MUSIC. The Synchrosqueezing transform (SST) (Daubechies and Maes 1996; Thakur and Wu 2011; Daubechies et al. 2011) is a post-processing method to time-scale (Wavelets) or time-frequency (Fourier) signal transforms. Synchrosqueezing reassigns coefficients in scale or frequency in order to reduce their uncertainty at discrete points in time.

2 Materials and Methods

2.1 Animal Model and Anaesthesia

The study was approved by the governmental ethical board for animal research (Landesamt für Landwirtschaft, Lebensmittelsicherheit und Fischerei, Mecklenburg-Vorpommern, Germany; No: 7221.3-1-037/19, 29 August 2019) and was carried out in accordance with the EU-directive 2010/63/EU and the Animal Research: Reporting of In Vivo Experiments guidelines 2.0 (ARRIVE 2.0) (Müller-Graf et al. 2021). Six healthy German Landrace pigs (24.4–48.3 kg, 12–15 weeks old) were cared for and premedicated according to internal standards of the Institute for Experimental Surgery at Rostock University Medical Centre. Animals were given free access to standard laboratory chow and water. The initial state (animals anesthetized, prior to intervention) served as control; therefore, no randomisation was needed. The investigators were not blinded. For premedication animals received an intramuscular injection of 8 mg/kg body weight azaperone and 20 mg/kg body weight ketamine. Two peripheral venous catheters were placed in the veins of both ears.

After preoxygenation, anaesthesia was induced using 0.2 mg fentanyl, 100 mg propofol , 4 mg pancuronium and maintained by continuous intravenous infusion of 4–8 mg $kg^{-1}h^{-1}$ propofol, 5–10 μg $kg^{-1}h^{-1}$ fentanyl, 6.4 mg h^{-1} pancuronium and 0.1 mg $kg^{-1}h^{-1}$ midazolam The pigs were intubated endotracheally (ID 7.0 mm) and mechanically ventilated in a pressure-controlled mode using a Dräger Primus ventilator with tidal volumes of 6 mL kg^{-1} and a PEEP of 5 mbar. Respiratory rate was adjusted to maintain end-tidal partial pressure of CO2 at 5 ± 0.4 kPa.

2.2 Data acquisition

The EIT data was acquired with the EIT Pioneer Set (Sentec AG, Landquart, Switzerland) using 32 electrodes, at a frame rate of 47.68 Hz. The other data series were acquired at 1 kHz using bridge transducer amplifiers in combination with dedicated hard- and software (PowerLab 16/35, and LabChart 8, both ADInstruments, Dunedin, New Zealand). Stored data was exported from LabChart into a MATLAB-compatible formatand synchronized in time with the EIT frames.

2.3 Signal processing

The spectral analysis of the EIT signal can be either carried out on the raw data in electrode space or in image space after reconstruction, respectively. In this work, the Fourier-based Synchrosqueezing transform (Oberlin et al. 2014) is applied. We consider a time signal $x(t)$ out of the EIT measurement series, either obtained from the heart region of subsequent reconstructed images or the time series from one of the insertion/measurement electrode pairs in electrode space. The Fourier transform of that signal $x(t)$ is given by

$$X(f) = \int_{-\infty}^{\infty} x(t) \mathrm{e}^{-j2\pi f t} \mathrm{d}t \tag{1}$$

Adding a sliding window $g(t)$ to the formulation leads to the local spectra of short-time Fourier transform (STFT):

$$X_f(f,t) = \int_{-\infty}^{\infty} x(\tau) g(\tau - t) \mathrm{e}^{-j2\pi f(\tau - t)} \, d\tau \tag{2}$$

The resulting spectrogram $|X_f(f,t)|$ spans the time-frequency (TF) plane defined by observations within the time intervals $g(\tau - t)$ with respect to frequencies f in order to follow instationary processes.

The Synchrosqueezing transform models the input signal $x(t)$ as a multicomponent signal of the type

$$x(t) = \sum_{k=1}^{K} x_k(t) = \sum_{k=1}^{K} A_k(t) \mathrm{e}^{-j2\pi\phi_k(t)}, \tag{3}$$

where $A_k(t)$ and $\phi_k'(t)$ are the instantaneous amplitudes and frequencies, respectively. Under the assumption of slow variation of these parameters, an approximation of $\tilde{x}(t)$ can be formulated that is based on a sum of pure waves:

$$\tilde{x}(t) = \sum_{k=1}^{K} A_k \mathrm{e}^{-j2\pi\left[\phi(t) - \phi_k'(\tau - t)\, t\right]}, \tag{4}$$

The corresponding STFT $X_f(f,t)$ becomes:

$$\tilde{X}_f(f,t) = \sum_{k=1}^{K} x_k(t) \hat{g}(f - \phi_k'(t)). \tag{5}$$

A multicomponent signal $x_k(t)$ is concentrated in TF plane around dominant frequencies (called ridges), defined by $f(t) = \phi_k'(t)$. With frequencies $\phi_k'(t)$ separated well beyond the support of the frequency neighborhood $\hat{g}(f)$, each mode occupies a distinct domain of the TF plane, allowing their detection, separation and reconstruction (Oberlin et al. 2014).

Given $\tilde{X}_f$, the SST moves coefficients in $\tilde{X}_f(f,t)$ according to the map $(f,t) \mapsto (\hat{\eta}_f(f,t), t)$, where $\hat{\eta}_f$ is the local instantaneous frequency at time t and filtered at frequency f, defined as

$$\hat{\eta}_f(f,t) = \frac{1}{2\pi} \frac{\partial \arg \tilde{X}_f(f,t)}{\partial t}. \tag{6}$$

This expression is a local approximation of the instantaneous frequencies $\phi_k'(t)$. In closed form, the Synchroqueezed TF plane $T_f(\eta, t)$ is mapped from $\tilde{X}_f(f,t)$ by:

$$T_f(\eta, t) = \frac{1}{g(0)} \int_{-\infty}^{\infty} \tilde{X}_f(f,t) \delta\left(\eta - \hat{\eta}_f(f,t)\right) \, df \tag{7}$$

Given that the sliding window $g(\tau - t)$ for the STFTs was parameterized with a step size Δt of one sample, then both $\tilde{X}_f(f,t)$ and the remapped result $T_f(\eta, t)$ are available at a temporal resolution matching the EIT frame sampling rate. For the spectral resolution in f, η is an application-specific parameter which is no longer strictly tied to the conventional tradeoff in time-frequency resolution.

Following the Synchrosqueezing mapping, the relevant signals or their frequencies may be extracted. In case of EIT heart rate detection, we employ an initial estimate and apply a local search algorithm across the frequency range for each time step. Some frequency coefficients below the threshold of the Synchrosqueezing remapping algorithm and windowing effects in presence of abrupt rate changes may lead to mis-detection of the true local maximum.

These potential issues can be mitigated by a lowpass filter $g_l(\eta)$ on the frequency coefficients, whose support follows the same constraint on separated frequencies $\phi_k'(t)$ that applies to $\hat{g}$.

$$D_f(\eta, t) = |T_f(\eta, t)| * g_l(\eta) \tag{8}$$

From the resulting spectrogram $D_f(\eta, t)$, the instantaneous frequency corresponding to the heart rate can be extracted iteratively across time within the local neighborhood L with the previous estimate $\hat{R}_H(t - \Delta t)$ as center point.

$$\hat{R}_H(t) = \underset{\eta_1 \in [-L, L]}{\arg\max} \; D_f\left(\eta_1 + \hat{R}_H(t - \Delta t), t\right) \tag{9}$$

3 Results

Fig. 1a shows the initial STFT over 3812 EIT frames. A single insertion/measurement electrode pair from the dorsal region of the subject was selected. The sliding window was set to a length of 701 samples or 14 seconds. The observed sequence begins with 20 cycles/minute ventilated breathing, followed by 40 seconds apnea. Afterwards, ventilation was resumed. The subject's heart rate is visible around the 1 Hz mark. Due to varying heart rate and an STFT window stretching over several heart beats, the instantaneous heart rate cannot readily be determined from this initial spectrogram.

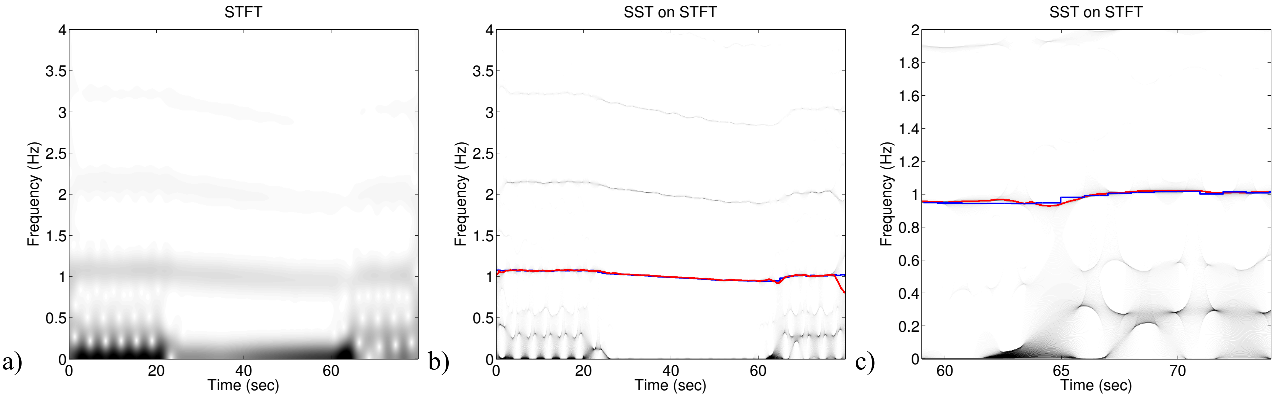

Figure 1: a) STFT with a 701 point Hermitian sliding window over 80 seconds, b) Synchrosqueezing result after post-processing the STFT. Overlayed instantaneous heart rate from ECG (blue) and EIT Synchrosqueezing (red), c) Closer zoom into the plot from b)

After post-processing the spectrogram with the Synchrosqueezing process, the instantaneous rates of ventilation and perfusion cycles are concentrated into distinct maxima of fundamental frequencies and their harmonics (fig. 1b). The synchronously captured ECG based heart rate (blue) closely matches the estimate from the SST output spectrogram (red), with a mean square difference (MSD) of 0.02 BPM or 0.0003 Hz.

In contrast to the ECG based approach whose estimated heart rate only changes at each new detected heartbeat, the Synchrosqueezed EIT based approach is able to follow changes of the heart rate closely and exhibits a smooth curve (fig. 1c). The average MSD across multiple 60 sec. EIT measurements was found at 0.03 BPM in our evaluation.

The previous experiments were conducted on EIT sequences with active ventilation. The significantly higher amplitudes of the ventilation signal in comparison to the perfusion signal also extend over the harmonics. The same challenges applying to signal separation by filtering are also of relevance for the SST.

Therefore, the following experiments were conducted with EIT data after suppression of the ventilation component by using the method outlined in (Richter et al. 2021). A case of abruptly changing heart rate is depicted in fig. 2, where a saline Bolus injection was applied at 20 seconds into the measurement in a subject of already elevated heart rate and irregular ECG.

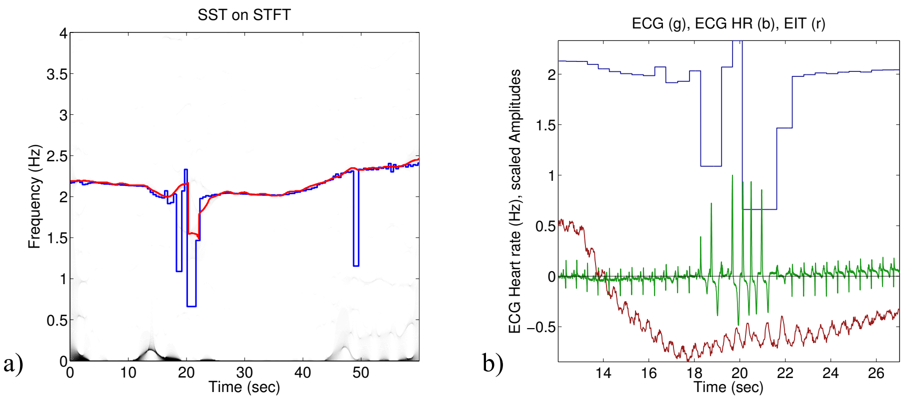

Figure 2: a) Synchrosqueezing result of EIT sequence with suppressed ventilation and a saline Bolus injection around the 20s mark. Overlayed instantaneous heart rate from ECG (blue) and EIT Synchrosqueezing (red), b) corresponding time signals of EIT (red), ECG (green) and ECG derived heart rate (blue)

In this case, disturbances during the saline Bolus injection led to difficulties for the ADInstruments software towards ECG based heart rate estimation, while the EIT Synchrosqueezing based approach returned plausible results in such corner cases.

Another example of a healthy subject is shown in fig. 3a, where the heart rate increases during Bolus injection. Corresponding ECG and EIT time signals are depicted in fig. 3b.

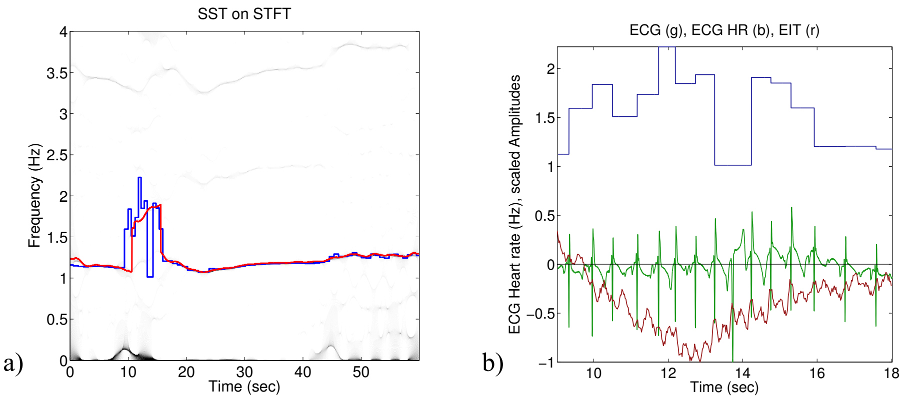

Figure 3: a) Synchrosqueezing result of EIT sequence with suppressed ventilation and a saline Bolus injection around the 10s mark. Overlayed instantaneous heart rate from ECG (blue) and EIT Synchrosqueezing (red), b) corresponding time signals of EIT (red), ECG (green) and ECG derived heart rate (blue)

4 Discussion

The experimental results suggest that Synchrosqueezing appears to be a viable alternative to classic heart rate estimation methods. Since the SST is invertible, the option of consecutive time and frequency domain signal processing is retained. Candidate operations in this area include signal separation of ventilation and perfusion or noise suppression. The instantaneous frequencies may also be used as steering vectors for ensemble averaging in time domain.

Potential challenges towards SST based frequency estimation are present at the beginning and near the end of the observation interval. This is depicted in fig. 1b, where the frequency localization is challenged especially at the end of that sequence. The underlying reason is the sliding window which contains less samples from the input signal towards the corners of the observation interval. As a consequence, the estimator is not consistent and will exhibit higher variance in those parts of the spectrogram.

As outlined in eq. 5, the success of the SST depends on the separation of signal components. Frequency localization is challenged in cases where the harmonics of the ventilation signal are near to the fundamental of the perfusion signal in the time-frequency plane. An example for that constraint can be seen in fig. 1c, near the 65 second time mark.

5 Conclusions

In this paper, we proposed a method to estimate a subject's heart rate directly from EIT frames by using the Fourier domain Synchrosqueezing transform. A prominent benefit of this approach is the sample-by-sample temporal resolution of the Synchrosqueezed output spectrum whose frequency resolution is a parameter that can also be adjusted to meet the application requirements. This flexibility is a significant bonus over the classic STFT and also parametric spectral estimation methods like MUSIC or ESPRIT.

Experimental results suggest that this method of heart rate detection is fairly robust in presence of noisy source signals. Potential applications include signal separation, noise reduction and triggering for ensemble averaging.

References

Daubechies, I. and Maes, S. A nonlinear squeezing of the continuous wavelet transform based on auditory nerve models. In *In Wavelets in medicine and biology (eds A Aldroubi, M Unser)*, pages 527–546. CRC Press, Boca Raton, FL, 1996. doi: 10.1201/9780203734032.

Daubechies, I., Lu, J., and Wu, H.-T. Synchrosqueezed wavelet transforms: An empirical mode decomposition-like tool. *Applied and Computational Harmonic Analysis*, 30(2):243–261, 2011. ISSN 1063-5203. doi: https://doi.org/10.1016/j.acha.2010.08.002.

Deibele, J. M., Luepschen, H., and Leonhardt, S. Dynamic separation of pulmonary and cardiac changes in electrical impedance tomography. *Physiological Measurement*, 29(6):S1–S14, jun 2008. doi: 10.1088/0967-3334/29/6/s01.

Jang, G. Y., Jeong, Y. J., Zhang, T., Oh, T. I., Ko, R.-E., Chung, C. R., Suh, G. Y., and Woo, E. J. Noninvasive, simultaneous, and continuous measurements of stroke volume and tidal volume using EIT: feasibility study of animal experiments. *Scientific Reports*, 10(1), July 2020. doi: 10.1038/s41598-020-68139-3.

Müller-Graf, F., Merz, J., Bandorf, T., Albus, C. F., Henkel, M., Krukewitt, L., Kühn, V., Reuter, D., Vollmar, A., Pulletz, S., Böhm, S. H., Reuter, D. A., and Zitzmann, A. Correlation of Pulse Wave Transit Time and Pulmonary Artery Pressure in a Porcine Model of Pulmonary Hypertension. *Biomedicines 2021*, 9(9):1–14, 2021. doi: 10.3390/biomedicines9091212.

Oberlin, T., Meignen, S., and Perrier, V. The fourier-based synchrosqueezing transform. In *2014 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, pages 315–319, 2014. doi: 10.1109/ICASSP.2014.6853609.

Richter, H., Krukewitt, L., Müller-Graf, F., Merz, J., Zitzmann, A., and Kühn, V. Signal separation in raw eit measurements. In *Proceedings of the 21st International Conference on Biomedical Applications of Electrical Impedance Tomography*, page 38. jun 2021.

Thakur, G. and Wu, H.-T. Synchrosqueezing-based recovery of instantaneous frequency from nonuniform samples. *SIAM Journal on Mathematical Analysis*, 43(5):2078–2095, Jan 2011. ISSN 1095-7154. doi: 10.1137/100798818.

Vonk Noordegraaf, A., Janse, A., Marcus, J. T., Bronzwaer, J. G. F., Postmus, P. E., Faes, T. J. C., and de Vries, P. M. J. M. Determination of stroke volume by means of electrical impedance tomography. *Physiological Measurement*, 21(2):285–293, may 2000. doi: 10.1088/0967-3334/21/2/308.