

Cardiac activity measurement from video signals of the human skin in ultra-high-field magnetic resonance imaging

Nicolai Spicher^{1,2}

Abstract: Ultra-high-field magnetic resonance imaging (MRI) with field strengths ≥ 7 Tesla comes with many benefits concerning image quality such as increased signal-to-noise ratio (SNR) as well as high spatial and temporal resolution. However, there are still many technical challenges encountered, impeding its full potential. For example, conventional contact-based methods for cardiac monitoring and triggering such as pulse oximetry and electrocardiography are limited by an increased error rate at higher field strengths. In this paper, we give an overview on our works in developing video-based, contact-free, real-time methods to overcome these limitations based on recent findings in remote vital sign measurement.

Keywords: Biomedical engineering, biosignal and image processing, remote vital sign measurement, magnetic resonance imaging, pulse oximetry, photoplethysmogram, real-time applications

1 Motivation and problem statement

MRI is an established medical imaging modality that allows for obtaining an accurate depiction from the inside of the human body without the application of ionizing radiation. If not handled correctly, physiological motion from cardiac activity can reduce image quality significantly. In clinical practice, the conventional way to reduce these effects is by incorporating pulse oximetry (PO) or electrocardiography (ECG) for image acquisition ("triggering") according to the heart beat of the patient: Images are acquired at the same phase of consecutive cardiac cycles and therefore the object in the image (e.g. an artery) is always at an approximately similar position and the image is free of motion artefacts.

ECG uses electrodes attached to the skin for measuring the electrical activity of the heart. In contrast, PO measures the cardiac activity indirectly by detecting changes in blood volume. The probe passes light throughout the finger or earlobe and measures the transmitted light intensity, resulting in a photoplethysmogram (PPG). However, both contact-based approaches are limited by several constraints: The PO probe is susceptible to motion artefacts, its application areas are limited, and during long-time examinations the perfusion of the hands can decrease so far that the signal is lost. ECG is more robust to patient movement, but their placement requires medical staff. In addition, magnetohydrodynamic effects falsify ECG measurement, especially during ultra-high-field MRI [Sn09]. In this context, a 12-lead ECG in combination with independent component analysis [Kr13], and

¹ University of Applied Sciences and Arts Dortmund, Department of Computer Science, Emil-Figge-Str. 42, 44227 Dortmund, nicolai.spicher@fh-dortmund.de

² University Duisburg-Essen, Erwin L. Hahn Institute for Magnetic Resonance Imaging, Kokereiallee 7, 45141 Essen

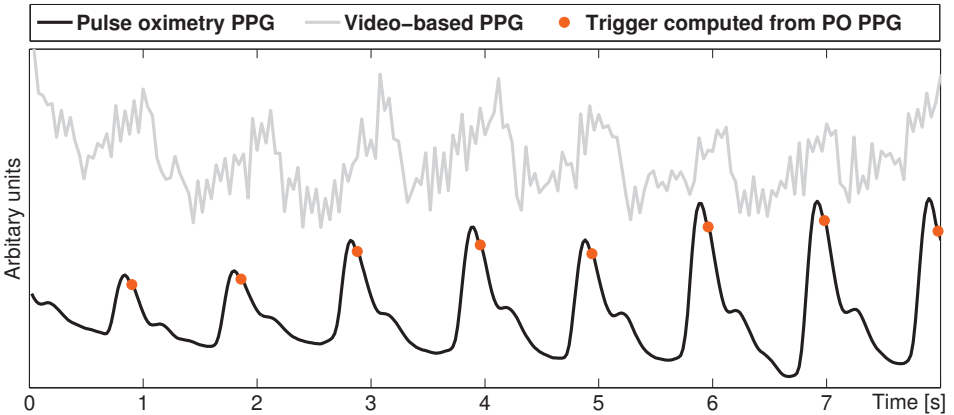


Fig. 1: Cardiac activity measured from a subject using a conventional PO probe (black curve) and a video signal recorded with a MR-compatible camera (gray curve). The latter is obtained by computing the mean pixel intensity in a ROI positioned on a volunteers forehead over time. Red dots mark trigger points that were determined from PO by the MR vendor-provided software and were sent to the scanner for image acquisition.

an optical microphone [Fr10] have been proposed which achieve promising results, but also increase patient preparation time significantly.

2 Problem solving approach

Recent findings in remote vital sign monitoring have shown that the cardiac activity can be estimated from videos of the human skin recorded with video cameras under ambient illumination [ST16]. The measured intensity variations of the skin contain a subtle signal, resulting from dermis deformation caused by transmural arterial pressure changes, which is similar to a PPG measured by PO [Ka15]. Due to the subtleness of this video-based PPG (vPPG), which can not be perceived by naked eye, it is common to increase SNR by examining a spatially pooled region-of-interest (ROI) instead of single pixels. Fig. 1 displays this kind of signal and a PPG obtained in parallel by conventional finger PO. As can be seen, both signals are similar although the SNR of the vPPG is significantly lower.

We pursue to transfer this video-based and contact-free technique for cardiac activity estimation and apply it to subjects undergoing ultra-high-field MRI examinations with the aim to overcome the described limitations of contact-based hardware. However, many methods from literature cannot be used without adjustments in this context because (1) MR-compatible cameras have a significantly lower performance than most off-the-shelf digital cameras, (2) real-time processing of the video signal is required, (3) patients undergoing examinations are potentially not cooperative or not able to avoid movement, and (4) the illumination conditions inside the MR bore are poor which additionally reduces video quality.

3 Related work

To the knowledge of the authors, in 2005 Wieringa et al. were the first that acquired a remote vPPG using a camera and designated LED illumination [WMv05]. Subsequently, Takano [TO06] and Verkruyse [VSN08] were the first that by made use of this signal for vital sign monitoring with ambient illumination only by analyzing pooled pixel intensities in a ROI over time and performing spectral analysis for heart rate (HR) measurement. Considering the visualization of the vPPG signal, Kamshilin et al. proposed an algorithm for the pseudo-colors visualization of the blood perfusion [Ka11] and Wu et al. proposed an algorithm called "Eulerian Video Magnification" (EVM) for the amplification of subtle motions in videos that can be used to photo-realistically visualize the flow of blood [Wu12]. Recently, elaborate algorithms for HR estimation from vPPG signals recorded with color cameras in fitness [dJ13] or office settings [MGP14, WSd15] have been presented.

Due to the highly specialised character of applying this methods in MRI, the body of research is rather small in this field. Yang et al. estimated the HR of a subject in a mock MRI scanner but applied a conventional digital camera and did not measure a ground truth modality as reference [Ya14]. Maclaren et al. applied an MR-compatible camera inside the MR bore with additional illumination from an LED. They processed the obtained videos offline by using frequency filtering in order to obtain the vPPG signal as well as respiratory information [MAB15] [Ma14]. Pulse oximetry and a respiratory belt were used as ground truth and closely resembled the filtered vPPG signals.

4 Research plan

In the following, we denote a signal, obtained over time t by mean pixel computation in a ROI centered on human skin, $vPPG$. It exhibits subtle color intensity variations that can be roughly approximated as a cosine wave with frequency f , associated to the HR, and phase ϕ . This sinusoid allows to approximate the stages of the cardiac cycle from the outflow of blood (low mean value in ROI) to the influx of blood (high mean value), and the reoccurring outflow of blood (low mean value). However, due to the subtleness of this signal, it is considerably degraded by noise $N(t)$ introduced by the patient (e.g. motion artefacts) and noise $M(t)$ introduced by the limitations of the used camera:

$$vPPG(t) \approx \cos(2\pi ft + \phi) + N(t) + M(t) \quad (1)$$

We seek to estimate f and ϕ and use them for two tasks: HR monitoring of subjects undergoing MRI examination and computation of trigger points for MR image acquisition.

5 Preliminary results and current status

Inspired by the works from Wu et al. [Wu12], initial experiments began in 2014. Since then, the experimental set-up as well as the algorithms have been revised extensively:

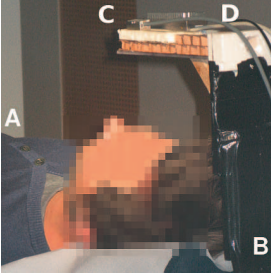


Fig. 2: Current camera set-up applied to a volunteer (A) outside the MR bore with the patient table in home position. The custom-build stand (B) holds the low-speed (C) and high-speed (D) MR-compatible cameras. The set-up can be applied inside the bore without modification.

Set-up As initially no MR-compatible camera was available at the 7T MRI site, preliminary experiments were conducted using an off-the-shelf camera (RGB, 640x480, 30 FPS) outside the 7T scanner bore and using a MR-compatible camera (B/W, 720x576, 25 FPS) during a routine 3T MRI examination on a volunteer. In both cases, the ROI was centered on a the volunteers' finger and no particular illumination instead of room lighting was used [Sp14]. We observed that (1) the SNR of $vPPG$ is rather low on the finger, (2) the low illumination inside the MR bore reduces SNR additionally, and (3) the subjects tend to move the finger.

Hence, when the MR-compatible camera (B/W, 720x576, 25 FPS) was available at the 7T site, we built a stand that was used to install the camera above the well-perfused subject's head. Additionally, a video projector was placed at the end of the MR bore and used to provide illumination [Sp15a] [Sp15b]. Recently, we added a high-speed MR-compatible camera prototype (up to 1076 FPS) to the set-up which allows us to evaluate the performance increase [Sp16]. Fig. 2 shows the current experimental set-up.

Algorithm Since beginning of the project, algorithms were developed using C++11 as glue code, OpenCV¹ for image processing, and ROOT² for mathematical computations.

We began our research using the EVM algorithm, which allows to magnify a certain frequency range in videos [Wu12], as a starting point. We developed a real-time feasible implementation that first estimates the subjects' HR frequency and then magnifies it in the videos using EVM. Videos were processed by our implementation, the $vPPG$ signals obtained from the magnified videos were compared to PO PPG acquired with the MR-compatible probe and we observed that both signals correlated well [Sp14]. However, our further research revealed that the EVM algorithm is occasionally vulnerable to Gibbs phenomenon when using short video signals which prohibits to obtain accurate results for our application that depends on current cardiac information.

Therefore, we decided to develop a more lightweight algorithm: A real-time algorithm processing raw $vPPG$ signals was developed that estimates f of the subject by detecting the peak in the Fourier spectrum associated with the cardiac activity and then estimates ϕ of this component for trigger point computation [Sp15a] [Sp15b].

¹ <http://www.opencv.org/>

² <https://root.cern.ch/>

Results Using this algorithm based on spectral analysis and the set-up shown in Fig. 2, we first conducted a study with eight subjects in- and outside the MR bore using the algorithm for HR estimation based on f . We compared its performance to ECG and PO which suggests that the video-based approach is feasible but still inferior in accuracy compared to contact-based methods. As results outside the bore achieved significantly better results, we assumed that the illumination conditions inside the bore still pose a challenge for accurate $vPPG$ acquisition although we increased illumination by using a video projector [Sp15b].

For one volunteer, we used our algorithm for trigger point computation based on ϕ and showed that our approach outperforms PO triggering in case of PO interference caused by gradient vibrations during 7T MRI. However, $vPPG$ SNR decreases during head motion and requires additional measures (e.g. motion correction) to increase performance [Sp15a]. Recently, we applied the high-speed camera and investigated how accurately one can approximate the PO PPG from $vPPG$. We observed that using a simple filtering technique, physiological peaks that are clearly visible in PO PPG (Fig. 1 low amplitude peaks following the high amplitude peaks) but not in the raw $vPPG$ can be made visible [Sp16].

Our current aim is to apply our video-based MRI triggering technique to a larger group of subjects and compare its performance to contact-based methods.

Acknowledgments

This project is performed in collaboration with *Prof. Dr. Markus Kukuk*¹, *Dr. Stefan Maderwald*², and *Prof. Dr. Mark E. Ladd*^{2,3}, and the author thanks all three of them for fruitful discussions and their valuable advices.

References

- [dJ13] de Haan, Gerard; Jeanne, Vincent: Robust Pulse Rate From Chrominance-Based rPPG. *IEEE Transactions on Biomedical Engineering*, 60(10):2878–2886, 2013.
- [Fr10] Frauenrath, Tobias; Hezel, Fabian; Renz, Wolfgang; de Geyer d’Orth, Thibaut; Dieringer, Matthias; von Knobelsdorff-Brenkenhoff, Florian; Prothmann, Marcel; Schulz Menger, Jeanette; Niendorf, Thoralf: Acoustic cardiac triggering: a practical solution for synchronization and gating of cardiovascular magnetic resonance at 7 Tesla. *Journal of Cardiovascular Magnetic Resonance*, 12(67), 2010.
- [Ka11] Kamshilin, Alexei A.; Miridonov, Serguei; Teplov, Victor; Saarenheimo, Riku; Nippolainen, Ervin: Photoplethysmographic imaging of high spatial resolution. *Biomedical Optical Express*, 2(4):996–1006, 2011.
- [Ka15] Kamshilin, Alexei A.; Nippolainen, Ervin; Sidorov, Igor S.; Vasilev, Petr V.; Erofeev, Nikolai; Podolian, Natalia P.; Romashko, Roman: A new look at the essence of the imaging photoplethysmography. *Scientific Reports*, 5(10494), 2015.
- [Kr13] Krug, Johannes W.; Rose, Georg; Clifford, Gari D.; Oster, Julien: ECG-based gating in ultra high field cardiovascular magnetic resonance using an independent component analysis approach. *Journal of Cardiovascular Magnetic Resonance*, 15(104), 2013.

³ Deutsches Krebsforschungszentrum (German Cancer Research Center, DKFZ), Division of Medical Physics in Radiology, Im Neuenheimer Feld 280, 69120 Heidelberg

- [Ma14] Maclaren, Julian; Aksoy, Murat; Ehrl, Jakob; Saranathan, Manojkumar; Bammer, Roland: Simultaneous monitoring of cardiac and respiratory signals using a markerless optical system. In: Proceedings of the 22nd Annual Meeting of the ISMRM. 2014.
- [MAB15] Maclaren, Julian; Aksoy, Murat; Bammer, Roland: Contact-Free Physiological Monitoring Using a Markerless Optical System. *Magnetic Resonance in Medicine*, 74:571–577, 2015.
- [MGP14] McDuff, Daniel J.; Gontarekand, Sarah; Picard, Rosalind W.: Improvements in Remote Cardiopulmonary Measurement Using a Five Band Digital Camera. *IEEE Transactions on Biomedical Engineering*, 61(10):2593–2601, 2014.
- [Sn09] Snyder, Carl J.; DelaBarre, Lance; Metzger, Gregory J.; van de Moortele, Pierre-Francois; Akgun, Can; Ugurbil, Kamil; Vaughan, John T.: Initial Results of Cardiac Imaging at 7T. *Magnetic Resonance in Medicine*, 61(3):517–524, 2009.
- [Sp14] Spicher, Nicolai; Brumann, Christopher; Kukuk, Markus; Ladd, Mark E.; Maderwald, Stefan: Eulerian Video Magnification for Heart Pulse Measurement in MRI Scanners. In: Proceedings of the 22nd Annual Meeting of the ISMRM. 2014.
- [Sp15a] Spicher, Nicolai; Kukuk, Markus; Ladd, Mark E.; Maderwald, Stefan: In vivo 7T MR imaging triggered by phase information obtained from video signals of the human skin. In: Proceedings of the 23rd Annual Meeting of the ISMRM. 2015.
- [Sp15b] Spicher, Nicolai; Maderwald, Stefan; Ladd, Mark E.; Kukuk, Markus: Heart rate monitoring in ultra-high-field MRI using frequency information obtained from video signals of the human skin compared to electrocardiography and pulse oximetry. In: *Current Directions in Biomedical Engineering*. volume 1, pp. 69–72, 2015.
- [Sp16] Spicher, Nicolai; Maderwald, Stefan; Ladd, Mark E.; Kukuk, Markus: High-speed, contact-free measurement of the photoplethysmography waveform for MRI triggering. In: Proceedings of the 24th Annual Meeting of the ISMRM. 2016.
- [ST16] Sun, Yu; Thakor, Nitish: Photoplethysmography Revisited: From Contact to Noncontact, From Point to Imaging. *IEEE Transactions on Biomedical Engineering*, 63(3):463–477, 2016.
- [TO06] Takano, Chihiro; Ohta, Yuji: Heart rate measurement based on a time-lapse image. *Medical Engineering & Physics*, 29:853–857, 2006.
- [VSN08] Verkruyse, Wim; Svaasand, Lars O.; Nelson, J. Stuart: Remote plethysmographic imaging using ambient light. *Optics Express*, 16(26):21434–21445, 2008.
- [WMv05] Wieringa, Fokko P.; Mastik, Frits; van der Steen, Antonius F. W.: Contactless multiple wavelength photoplethysmographic imaging: a first step toward "SpO2 camera" technology. *Annals of Biomedical Engineering*, 33:1034–41, 2005.
- [WSd15] Wang, Wenjin; Stuijk, Sander; de Haan, Gerard: Exploiting Spatial Redundancy of Image Sensor for Motion Robust rPPG. *IEEE Transactions on Biomedical Engineering*, 62(2):415–425, 2015.
- [Wu12] Wu, Hao-Yu; Rubinstein, Michael; Shih, Eugene; Guttag, John; Durand, Frédo; Freeman, William T.: Eulerian Video Magnification for Revealing Subtle Changes in the World. *ACM Transactions on Graphics*, 31(4), 2012.
- [Ya14] Yang, Shang-Yi; Huang, Hsiao-Hui; Liang, Chi-Wei; Tsai, Shang-Yueh; Huang, Teng-Yi: Noncontact physiological measurements using video recording inside an MRI scanner. In: Proceedings of the 22nd Annual Meeting of the ISMRM. 2014.