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Non-Contact Reflectance Photoplethysmography: Progress, Limitations, and Myths

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***Abstract*— Photoplethysmography (PPG) is a non-invasive method of measuring changes of blood volume in human tissue. The literature on non-contact reflectance PPG related to cardiovascular activity is extensively reviewed. We identify key factors limiting the performance of the PPG methods and reproducibility of the research as: a lack of publicly available datasets and incomplete description of data used in published experiments (missing details on video compression, lighting setup and subject's skin type), use of unreliable pulse oximeter devices for ground-truth reference and missing standard experimental protocols. Two experiments with 5 participants are presented showing that the quality of the reconstructed signal (1) is adversely affected by a reduction of spatial resolution that also amplifies the effects of H.264 video compression and (2) is improved by precise pixel-to-pixel stabilization.**

I. INTRODUCTION

The improvement of photodetector circuits in the last two decades encouraged research in non-contact monitoring techniques of human vital functions. Methods processing output of standard image sensors deliver heart- and blood-related measurements comparable with the ones extracted from purpose-built devices [25].

Plethysmography, from Greek $\pi\lambda\eta\theta o\varsigma$ (fullness) and $\gamma\rho\alpha\phi\acute{o}\varsigma$ (to write) [6], measures changes in volume within a living body. Historically, it was used to study the peripheral circulation of blood. It was replaced in this role by photoplethysmography (PPG) that performs the measurements remotely with a photosensitive device. PPG was first described in 1936 by Molitor and Kniazuk [37]. Today, PPG is a synonym for non-contact monitoring of cardiovascular activity [2]. PPG based devices are used to monitor human heart rate and estimate the level of oxygen in blood.

PPG requires two components, a light source and a photodetector [20]. Based on the arrangement of the light source, tissue, and the detector, two forms are recognized. Transmittance PPG (tPPG) and reflectance PPG (rPPG). In tPPG, the photodetector captures light transmitted through the body tissue, in rPPG, the reflected light is recorded. Both forms exist in contact and non-contact version. The exact origin of the recovered PPG signal is not clear [36].

The best known application of tPPG is the pulse oximeter. Pulse oximetry extracts peripheral arterial oxygen saturation (SpO_2) as the ratio of amplitudes of the tPPG signal at two wavelengths. It is generally agreed that the observed phenomenon is a varying proportion of oxygenated and deoxygenated blood. Intensive studies lead to a widespread clinical application. There is a broad spectrum of commercially available clinically certified pulse oximeters.

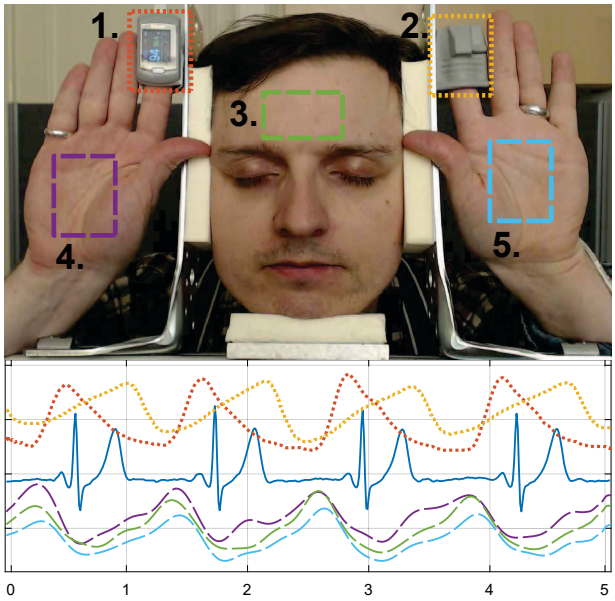

Fig. 1. PPG data acquisition. Top: experimental setup. Bottom: 5 seconds of reference electrocardiogram – navy blue, distinguishable by the QRS-complex, contact transmittance PPG – measured by oximeters on the left and right index fingers (color-coded like areas 1. and 2.), and non-contact reflectance PPG estimated from the video in areas 3., 4., and 5. (NrPPG). The NrPPG signal is high and low pass filtered, and amplified 500 times. Arbitrary units. The head is stabilized in a custom made frame.

Historically, the research in the rPPG field was limited by a low signal-to-noise (SNR) ratio of the rPPG signal. With the recent improvements of the spatial resolution and sensitivity of photodetectors (especially CCD and CMOS chips), a new wave of rPPG related research emerged. Researches moved from purpose-built contact measuring devices to general purpose non-contact rPPG (NrPPG) cameras. New approaches utilizing modern photodetectors will be discussed in Sec. IV-D. The community have not reached consensus on the physical principles of rPPG [51]. Two hypotheses on the causes of the observed phenomenon are: optical density change within the tissue caused by arterial pulsations and local deformations of tissue caused by capillaries [27].

The contributions of this work are the following. Details affecting the performance of the NrPPG signal reconstruction are discussed and recommendations on its improvement are

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given: (1) stable, uniform and orthogonal lighting should be used, (2) subject's movement should be compensated, (3) lossless or no video compression method should be used. We focus in particular on the image and video processing methods. To the best of our knowledge, we are the first to examine how the reconstructed signal quality is influenced by video compression (H.264) of sequences with different spatial resolution and by the accuracy of pixel-to-pixel registration. The latest developments in the field are summarized. We note that clinical adoption of the NrPPG is hampered by poorly described datasets and experimental setup (including lighting setup, camera type, subject's skin type and video compression), and by absence of internationally recognized research methodology.

II. Related work

To the best of our knowledge, there are only four recent studies that review the rPPG research.

The work of Allen [2] is the earliest. Allen focuses on the clinical application of the PPG approaches and includes references to the rPPG as well. The rPPG is represented by several papers of subjects ranging from plastic surgery post-operative monitoring to oculoplethysmography, a non-contact method of detecting carotid occlusive arterial disease.

A more recent work of Liu et al. [31] tracks the rapid development of the rPPG approaches between years 2007 and 2012. Such development was likely caused by an introduction of cheap and relatively precise measuring devices, i.e. web cameras and alike. Liu concludes that although the NrPPG is comparable with the traditional contact tPPG systems it needs further improvement for the clinical use in terms of SNR.

A paper by Sun and Thakor [51], published in September 2015, provides a survey of a large body of the literature focused on contact and NrPPG methods, there referred to as imaging PPG. The differences between the discussed methods are shown on the different choices taken during the procedure of obtaining the rPPG signal. The authors conclude with a convincing statement that the NrPPG "will dramatically change our lifestyle in the near future".

The most recent work of Hassan et al. [19] from September 2017 provides a comparison of the heart rate estimation methods that employ a video recording. Authors provide review of the research performed both on illumination variance and ballistocardiographic motion based methods as discussed in Sec. V-A and they conclude that "non-invasive nature [of the NrPPG] opens possibilities for health monitoring towards various fields such as health care, telemedicine, rehabilitation, sports, ergonomics and crowd analytics".

Our study presumes the parameters derived from the NrPPG signal to be a surrogate for the parameters derived from an electrocardiogram. In 2013, Schafer et al. [47] concluded otherwise. However, Schafer et al. did not inspect NrPPG alone, but as one of the methods extracting a blood pulse. A study [25] from 2016 explores solely the NrPPG methods and concludes that, in terms of the recovered parameters, the NrPPG blood pulse signal may serve as an estimator of the electrocardiograph signal. We understand these findings as a sign of the NrPPG's suitability for a clinical application and we follow this paradigm in the following text.

III. Myths

A. Difficulty of PPG signal recovery

Advanced signal processing methods "needed to recover the [heart rate] information" are presented in [21]. Independent component analysis (ICA), principal component analysis, auto- and cross-correlation are compared and it is concluded that the most suitable method for the purpose of heart rate estimation is the ICA. Is there really a need of advanced signal processing methods for the heart rate estimation? As the heart rate in NrPPG approaches is obtained by processing a blood volume pulse (BVP) signal, we will discuss the BVP.

We identify four major causes that can make the BVP reconstruction task difficult. A video compression, a lighting setup, subject's movement and a skin type. The compression is discussed in Sec. IV-C.

Subject's movement may be mitigated by precise tracking and weighted spatial averaging [29]. Also a multi-imager array was proposed to improve the motion robustness of the NrPPG reconstruction [5], [13]. When the NrPPG imaging or deeper analysis of the BVP mechanisms is pursued, also the ballistocardiographic movement (BCG), i.e. the movement induced by the ballistic forces of the heart, must be accounted for [57] (see Sec. V-A).

By the lighting setup the light source position and intensity, both in space and over time, and its spectral composition are meant. Stationary, uniform and orthogonal lighting was shown to minimize artifacts in the NrPPG signal induced by the BCG movement – the variations in the light flux "amplify the modulation caused by subtle BCG motions" [40]. Effects of the light source spectral range were studied intensively [9], [10], [14], [30], [32], and a model predicting the relative NrPPG-amplitude was proposed [24] and verified [17]. Given the spectral composition of light, absorption spectrum of the oxygenated blood and dermis, and assuming 3% concentration of melanin, the authors were able to determine the spectral response of the NrPPG signal in the red, green, and blue channels of a camera.

The NrPPG signal-to-noise ratio is typically unfavorable. However, if properly captured, the BVP may be recovered by simple spatial averaging [1], [3], [29], [53], [57], [62], [65] as confirmed in our experiments.

Furthermore, we discourage from use of blind source separation methods (BSS) in the BVP signal reconstruction. When the BSS methods are employed, an assumption has to be made that a blood volume pulse is the only periodic component in the video [11]. This assumption is generally not true [17]. With cameras having the sampling rate close to the AC current frequency, if a common light source is used to illuminate the subject, aliasing effect might occur resulting in a corruption of the signal. Moreover, use of the BSS for the clinical application is limited by the fact that, as

to the order of the decomposed components, BSS methods are ambiguous [63], and a heuristic-driven selection must be performed. Instead of trying to recover the signal that might not even be present one should focus on handling the described points of failure.

B. Gold Standard

It was reported by numerous works (e.g. [1], [16], [21], [29], [39], [40], [43], [52], [53], [58], [60], [63]) that a signal obtained from a transmittance-mode pulse oximeter may serve as a gold standard in the evaluation of a NrPPG approach. However, the results of the research discussed bellow suggest that the reliability of the device is limited.

Mardirossian and Schneider showed that various physiological factors, heavy skin pigmentation including, are a source of the erroneous measurement of the device [23]. Trivedi et al. [55] examined five commercially available pulse oximeters during hypoperfusion, probe motion, and exposure to ambient light interference. None of the inspected devices performed the best under all conditions with failure rates varying from approximately 5% to 50%. Teng and Zhang [54] showed that the PPG signal obtained from a pulse oximeter is affected by a "contacting force between the sensor and the measurement site". Moreover, Palve in [45] concludes that a reflection-mode pulse oximeter gives more accurate readings under less than ideal conditions, which is agreed also by Wax in [61] and Nesseler in [41]. We consider these findings as a very good reason for abandoning the transmittance-mode pulse oximeter as a gold standard.

Due to the results of Buchs et al. [7], who showed that the PPG signal measured in the two index fingers and the two second toes differs for diabetic and non-diabetic subjects, and Nitzan et al. [42], who found that the pulse transit time is a function of a subject's age, we also consider the reflectance-mode pulse oximeter as compromised.

Based on the outcomes of the presented works and our own readings (see Fig. 1 on how a tPPG signal differs for two devices), we conclude that an electrocardiograph instead of the pulse oximeters should be used as the gold standard for evaluation of a particular NrPPG approach.

IV. Limitations

A. Methodology

In 2007, Allen complains about the absence of any internationally recognized standards for the clinical PPG measurement [2]. He also complains, that the published studies tend to be using "quite differing measurement technology and protocols," thereby limiting the reproducibility of the outcomes.

In 2013, Schafer and Vagedes review existing PPG studies in order to assess the accuracy of a pulse rate variability (PRV, see *Evaluation*) computed from a PPG signal as being an estimator of a heart rate variability [47]. They conclude that generally speaking, "quantitative conclusions are impeded by the fact that results of different studies are mostly incommensurable due to diverse experimental settings and/or methods of analysis".

In 2017, there are still no PPG measurement standards, the researchers in the NrPPG field use different experimental settings, the studies fail to report fundamental details about the setup of the experiments. With the NrPPG being a physiological measurement with ambitions on becoming a heart rate variability estimator for the clinical applications, this situation must change. Any research that pursue a clinical application must include the details about the three crucial parts of the experiment. The *dataset*, the *signal processing* method, and the *evaluation* of which the first and the last one are the root cause of the limited reproducibility and will be discussed.

a) Dataset: The input of the NrPPG approaches is a signal captured in time by a photodetector. As such, the sampling frequency, the spatial resolution, the sensor type, and the capture duration must be given. Also, as the recovered blood volume pulse signal depends on the optics attached to the capturing device [11], on the illumination [9], [30], [32], and on the skin-reflectance [10], [14], the specification of the optical setup, light sources and subject's skin must be included. When the skin is discussed, a widely accepted Fitzpatrick's chromatic scale [15] should be employed as in [1], [43], [56]. An extremely important is the information about the signal compression methods involved. We discuss this matter in Sec. IV-C.

b) Evaluation: An overview of the NrPPG research in [51] reveals that 35 out of 38 works use a heart rate related error measure. One might argue that such measure, especially when using a pulse oximeter as a gold standard, might not be the best choice – here the heart rate may be obtained by various approaches, e.g. by computing number of peaks detected in one minute of a PPG signal for every consecutive sample, or by calculating the heart rate from distances between a couple of peaks. In both cases, averaging of heart rates over a certain time window may be applied. Unfortunately, the peak detection algorithm and the averaging window length are not known for a particular device and its different setting was shown to have negative effects on the derived measures [8]. As discussed in Sec. III-B, an electrocardiograph synchronized with the capturing device should be preferred as a gold standard reference. There exists an already well-defined methodology for analysis of the heart rate variability (HRV) [12]. HRV expresses the variations of the distances between the peaks in the electrocardiogram. Its usefulness as a clinical research and diagnostic tool has been verified in numerous studies [47] and adopted by the NrPPG researchers as a pulse rate variability (PRV) [33], [34], [38], [44], [48], [50], i.e. a variation of cycle intervals detected from the BVP wave. Lately, a study showing the suitability of the PRV as being an estimator of the HRV was published [25].

B. Public Datasets

The NrPPG datasets are small, usually 1 to 20 subjects, and private. To the best of our knowledge, there is currently available only one public dataset [49]. Unfortunately, this dataset only contains ground truth in form of the PPG signal

and SpO2 readings captured from the clip pulse oximeter. As discussed in Sec. III-B, such ground truth signal is compromised and should not be used.

C. Compression

In this section, we discuss specifics of works that use videos as a container for the captured data.

Surprisingly, many published studies fail to describe the dataset used to perform the experiments. We believe that this failure comes from the fact that the researches are not completely familiar with details of storing the captured data in a video file.

A common denominator of the NrPPG studies is that they report the captured data as being stored with 3×8 bits in some kind of video format. Without specifying that the video signal was not compressed, this information is useless. Let us explain why. In [64] we read that the videos "were recorded in 24-bit RGB (with 8 bits per channel)", 25 frames per second. Also, a capturing device is introduced – a Handycam Camcorder (Sony HDR-PJ580V) with resolution of 1440×1080 pixels. However, this particular camcoder records the videos (at the best) in the MPEG-4 AVC/H.264 format with a bitrate up to 24 Mbps. MPEG-4 AVC/H.264 is a block-oriented motion-compensation-based video compression standard. This standard permits to employ several kinds of compression principles including inter frame compression. This particular compression method stores the frames as expressed in terms of one or more neighboring frames. In other words, there is an image at the beginning and at the end of some sequence. The images in between are reconstructed from the two images. In between, only data needed for the reconstruction are stored, not the whole images. Now, how much is 3×8 bits? In case of [64], we can record up to 25 Mbps information per second. With 25 frames per second, we have 1 Mb per frame, and inside a frame, we have 1440x1080 pixels. $1000000/(1440 \times 1080) \approx 0.64$, i.e. we ended up with 3×8 bits ≈ 0.64. In [22], the camera used is Sony XDR-XR500 recording in H.264, 1920×1080 pixels, 29.97 frames per second, and a bitrate up to 16 Mbps, i.e. the situation is even worse.

In [63] we read that the videos "were further compressed in mp4 format". A clear distinction between a compression and a format must be made. When one speaks about a video format, a video container is actually thought. A *container* or wrapper format is a metafile format specifying how different elements of data coexist in a particular file. A container does not describe how the data are encoded. So, there is no such thing as "mp4 format compression".

The influence of the compression on the quality of the NrPPG signal reconstruction was examined by McDuff et al. in [35]. The experiments were performed on combinations of different compression algorithms with different motion tasks. The two tested compression standards were H.264 and H.265. The videos were compressed with a different constant rate factor (CRF), a setting for which we cannot find a more precise description other than that it "control[s] the adaptive quantization parameter to provide constant video quality across frames" [35]. It is not a surprise we can't find a better description. The crucial information here is that both H.264 and H.265 are *standards*. In other words, H.264 is a sum of instructions on how to encode a video so an arbitrary H.264 decoder can process it. The standard only specifies a structure of the compressed stream and does not tell anything about its content, i.e. quality. That is a domain of encoder and since encoders are implementation specific, we have no guarantees of quality at all. McDuff et al. solve this by using a particular publicly available freeware implementation of the H.264 and H.265 standards, x264 and x265. But the message is clear – if a NrPPG signal reconstruction is pursued, only none or lossless compression is safe.

McDuff et al. also mentioned the subject of chroma subsampling, i.e. a method of reducing the number of samples used to represent chromacity. Although the chroma subsampling may be used to represent an amount of color information loss in a standard compression scheme, we would like to emphasize its role in the design of the capturing devices. The most common way of capturing an uncompressed signal is with use of a web camera. However, even if stored in a raw format, still the "quality" of the signal might vary for different capturing devices. The web cameras typically perform the chroma subsampling already on the hardware level, before the captured data is sent to the USB port. Therefore, we also find important to always include information whether there was any kind of "hardware" chroma subsampling present for a particular capturing device.

D. Taxonomy

Sun and Thakor [51] were the first to provide a detailed survey on the NrPPG methods, there referred to as imaging PPG. We consider this naming convention misleading. It suggests that there is something unique to the NrPPG approaches employing CMOS and CCD cameras. We find the only difference in the number of photodetectors performing the readings. It comes natural that any two methods that process the same type of signal coming from the same type of sensor should be in the same category. The fact that in one case only a single sensor and in the other millions of them are used should not play a role. Furthermore, the term is very similar to the "PPG imaging" (e.g. [46]). PPG imaging refers to a process of mapping spatial blood-volume variations in living tissue with a video camera [40]. Not surprisingly, there is a line of research by Kamshilin et al. [26], [28] in which the term imaging PPG is used when the PPG imaging is actually thought. Therefore we propose a taxonomy based on a clear distinction between the approaches.

We recognize **tPPG** and **rPPG** methods as described in Sec. I. These may be performed in either **contact** or **non-contact** manner. Also, one might be interested in **PPG imaging**, more precisely NrPPG imaging, or in a **BVP reconstruction**.

Inside the NrPPG branch, another important partitioning may be made. One group of approaches perform the NrPPG signal capture with an **ambient lighting**, the second contains studies using a **supplementary lighting**. This classification

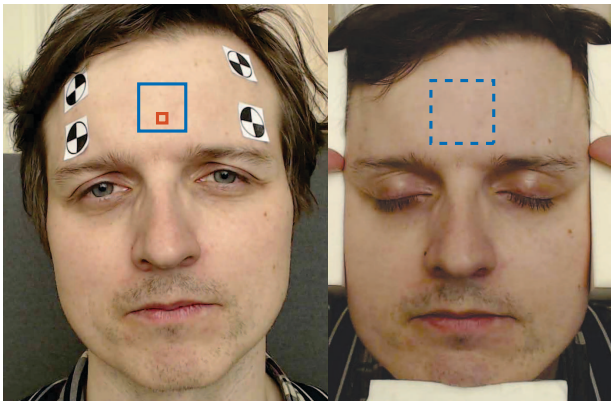

Fig. 2. Regions used in the registration and compression experiments (see Sec. VI). Solid blue – 75×75 px, solid orange – 15×15 px, dashed blue – 100×100 px.

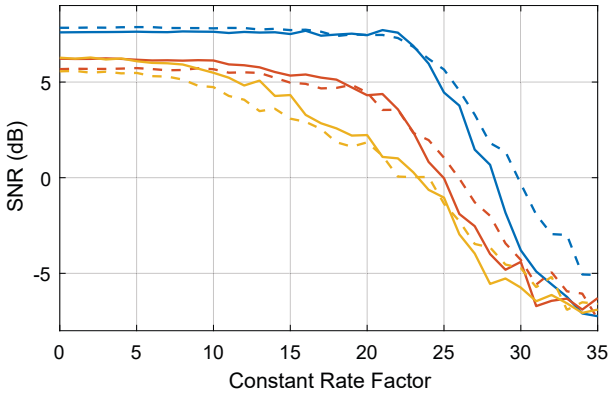

Fig. 3. NrPPG signal-to-noise ratio as a function of video compression level defined by the Constant Rate Factor; average for 5 subjects. Results for 60 second videos with resolution 1920×1080 pixels (blue), downscaled to 878×494 pixels (orange) and to 434×234 pixels (yellow). Dashed lines – results with tracking stickers, full lines – with stabilized head, see Fig. 2 left and right respectively.

follows a line of research showing the importance of the light source spectral composition [9], [10], [14], [24], [30], [32].

V. Advances

A. Ballistocardiographic artifacts

Ballistocardiography (BCG) studies ballistic forces of the heart, i.e. the inertial forces induced by the blood pulsation. Balakrishnan et al. was the first to recognize the BCG movement of a human face in a video and demonstrated reconstruction of the BVP with a blind source separation based approach [4]. One of the recent works [18] uses a combination of the BCG movement and color information to reconstruct the BVP related measures. A key BCG study was performed by Moço et al. who inspected an extent to which the BCG artifacts, i.e. motion artifacts inflicted by cardiac activity, influence the PPG imaging techniques [40]. Contamination of BVP imaging maps was showed to be severe implicating that the BCG artifacts must be accounted for in any research in the NrPPG imaging field. Otherwise a misinterpretation of the results is at hand. In this matter a recently proposed new physiological model of the remote PPG proposed by Kamshilin et al. [27] was inspected and needs to be reexamined.

B. Motion handling

The biggest limitation of the existing NrPPG methods seems to be the inability to cope with the motion-induced artifacts in the captured signal. Recent approaches try to resolve this issue by increasing dimensionality of the signal, thus improving separability of the BVP signal from distortions caused by motion. We recognize two major research directions in this matter. The first is represented by [59]. Here the dimensionality of the measurement is increased algorithmically by decomposing the RGB-signals into different frequency bands. In the second, the dimensionality of measurement is increased physically, e.g. by using a 5-band camera as in [33]. Currently, the approaches based on the algorithmic principles are receiving more attention, probably because the price of the specialized hardware is high and its availability limited.

VI. Experiments

In order to verify conclusions of the discussed works, we carried out two experiments: 1) we examine the extent to which a precise registration affects the SNR of the NrPPG signal, 2) we study the impact of video compression on the NrPPG signal .

Our experiments were performed with 5 volunteers (4 male, 1 female) aged 22 to 30 years, all with Fitzpatrick skin type III. The subjects were informed about the purpose of the research and signed an informed consent. 60 seconds long videos were captured in 1920×1080 @ 29.97 fps to uncompressed YUV420 format, AVI container, by Logitech C920 web camera with a hardware chromatic subsampling 4:2:0. A single video size was approx. 7 GB. A tPPG signal from right index finger and an electrocardiograph signal was recorded by clinically certified two-electrode Viatom CheckMe$^{\text{TM}}$Pro. Clinically certified pulse oximeter Beurer PO 80 was used to record a tPPG signal from left index finger. Both devices were synchronized with the camera. In case of four subjects, the light source was an overcast light coming from a nearby window. In case of one subject, the light source was an indirect light coming from a standard 500W halogen light.

Two videos were recorded for each subject. In the first, four photogrammetric markers were attached to the subject's forehead and the subject was asked to sit calmly (see Sec. VI-A). In the latter, the subject's head was stabilized in a custom made frame (see Fig. 1) and the subject was asked to turn the palms to the camera (see Sec. VI-B).

To quantitatively asses the strength of the reconstructed signal we employ a signal-to-noise ratio introduced by [17]:

$$\mathrm{SNR} = 10 \cdot \log_{10}\left(\frac{\int_{f_1}^{f_2} \mathcal{P}_{\mathrm{NrPPG}}(f)\mathrm{d}f}{\int_{0.5}^{f_1} \mathcal{P}_{\mathrm{NrPPG}}(f)\mathrm{d}f + \int_{f_2}^{4} \mathcal{P}_{\mathrm{NrPPG}}(f)\mathrm{d}f}\right) \quad (1)$$

subject ID	1	2	3	4	5
15×15 px ROI					
not registered	1.70	-6.17	-2.74	1.88	-7.08
registered	5.47	-6.03	2.6	2.99	-6.42
75×75 px ROI					
not registered	8.88	-5.42	6.77	6.80	-6.59
registered	9.15	-5.34	7.39	7.52	-5.68

TABLE I

SIGNAL-TO-NOISE RATIO IN DECIBELS OF A NRPPG SIGNAL FOR 5 SUBJECTS. THE SIGNAL IS COMPUTED BY SPATIAL AVERAGING OVER THE GREEN CHANNEL OF REGIONS SHOWN IN FIG. 2. RESULTS BEFORE AND AFTER REGISTRATION OF THE REGIONS.

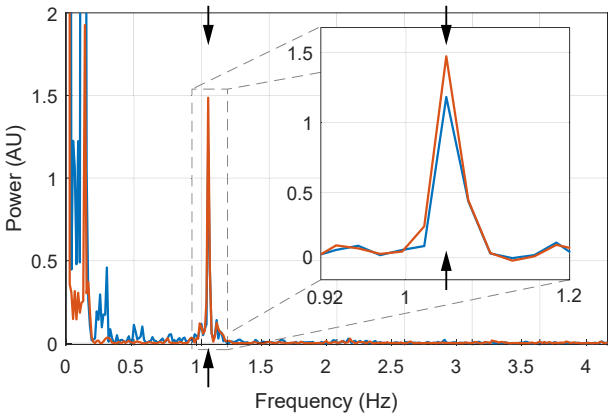

Fig. 4. Power spectral density of the NrPPG signal before (blue) and after (orange) registration. The signal computed by spatial averaging over a ROI of size 15×15 pixels in a green channel of a video. The true heart rate is marked by an arrow.

where $\mathcal{P}_{\text{NrPPG}}(f)\mathrm{d}f$ is the power spectral density (PSD) of the NrPPG signal, $f_1 = f_p - 0.15$, $f_2 = f_p + 0.15$, f_p is the median of heart rates computed from the peak-to-peak distances (measured in Hz). Before the signal's SNR is computed, the signal is weighted by the Hann window over the entire sequence to mitigate boundary effects.

A. Registration

Influence of quality of a NrPPG signal on precise tracking and registration is inspected. A video stabilized by pixel-to-pixel registration is compared to a non stabilized case. Videos with subjects having four photogrammetric markers attached to their foreheads were used (see Fig. 2). The stickers were manually set as interest points in the first frame, reference frame, and were tracked with MATLAB implementation of Lukas-Kanade tracker. Homography in each of the remaining frames was found between the reference and tracked points. The homographies were then used to register the pixels of the forehead over frames. A linear interpolation was used. Two rectangular regions of interest (ROI) were examined: 15×15 and 75×75 pixels. Both were positioned at the first frame of the video and the NrPPG signal was calculated by spatial averaging over a ROI in a green channel of every video frame.

A power spectral density of the NrPPG signal for subject five is shown in Fig. 4. In both cases the heart rate frequency is clearly visible. Without registration, we observe false frequencies with significant energy, while in the registered case the energy of these frequencies is reduced.

The results for all subjects are presented in Table I. After the registration, the SNR improves in all cases. The experiment suggests that a slight movement does not corrupt only NrPPG imaging as discussed in Sec. V-A but that it also corrupts the BVP signal. The corruption is probably caused by a combination of small ROI size and uneven texture of a skin. The smaller the ROI, the stronger the influence of the imperfections present on the skin surface. If an average over a small ROI is computed, the fluctuations of the image intensity, caused by the moving texture, produce a false signal. In a larger ROI, the fluctuations are averaged out. Note that the low SNR in case of subjects 2 and 5 is caused by a low power of the heart rate frequency compared to the other subjects.

B. Compression

In this experiment, effects of video compression on the strength of the recovered NrPPG signal are inspected. Every video file in the dataset was compressed with constant rate factor (CRF) settings varied from 0 to 35. Usually, the CRF is explained as a setting that induces "constant video quality", as opposed to the constant bit rate. CRF set to 0 means that a lossless compression is performed. FFmpeg program (version 2.8.11) was used to compress the videos with x264 encoder, a publicly available implementation of H.264 standard. The default CRF setting in x264 is 23. The NrPPG signal was obtained by spatial averaging over a ROI of size 100×100 pixels (see Fig. 2) in a green channel of a video. The videos with tracking markers were stabilized first (as described in Sec. VI-A).

Results are shown in Fig. 3. Originally, only experiments with the full resolution videos, i.e. 1920×1080 pixels (Full HD), were used. However, we did not experience a gradual decrease of the SNR reported by McDuff et al. who used videos with resolution 658×492 pixels. Therefore we performed the experiment also with videos downscaled to 878×494 and 434×234 pixels. Bi-cubic interpolation was used. The ROIs were scaled proportionally. Here the gradual SNR decrease is visible (see Fig. 3). Note that downscaling the video also lowered the SNR, and in case of Full HD videos, the SNR remained high until CRF 23. We conclude that reducing the video resolution negatively affects the SNR of the recovered NrPPG signal. Furthermore, steeper SNR loss is experienced when H.264 compression is applied to the videos with reduced resolution.

Next, we discuss results of Blackford and Estepp [5] who performed a similar experiment – they reduced resolution of videos from 658×492 to 329×246 pixels and concluded that there was "little observable difference in mean absolute error" between the two reconstructed BVP signals. We

identify four reasons why their conclusion differs from the results reported by us. First, independent component analysis, a powerful blind source separation (BSS) method, was used to obtain the NrPPG signal. We argue, that use of BSS methods in clinical application is not desirable (see Sec. III-A). Second, the ICA was computed with signals from five industry grade cameras that were part of a 9 camera array, each camera capturing images with resolution 658×492 pixels. An array of high quality cameras loses the benefits of NrPPG approaches built on cheap capturing devices. Third, a whole image, not a ROI, was used in their approach. Fourth, NrPPG signals recovered after downscaling were evaluated against original sized videos with mean absolute error.

An approx. 16 dB difference in the SNR reported by us and by McDuff et al. remains to be explained. First, McDuff et al. use the same experimental setup and approach as Blackford and Estepp. Second, they compute the SNR with a different, unspecified formula. Third, we compute the NrPPG signal by spatial averaging over a ROI from a single camera's green channel, they compute by applying ICA from a spatial average of whole image for red, green and blue channels from 5 cameras.

VII. CONCLUSIONS AND FUTURE WORKS

A. Conclusions

Two experiments with five participants were performed showing improvement of the NrPPG signal-to-noise ratio by a precise pixel-to-pixel registration, and deterioration of the signal-to-noise ratio due to the reduction of the resolution. The measurements illustrate unsuitability of the pulse oximeter as a ground truth reference, and show that advanced signal processing methods are not needed for the signal recovery. The factors limiting the research in non-contact reflectance photoplethysmography were identified as: (1) incomplete description of the dataset and experimental setup, (2) heterogeneous methodology, (3) absence of publicly available datasets, and (4) vague terminology. In a short summary of recent progress, the effects of ballistocardiographic movement on the NrPPG signal reconstruction, and handling of subject's motion by increase of input signal's dimensionality were discussed.

The generalization of the experimental results is limited by the small number of participants. Also, a decrease of the SNR after the reduction of the resolution might be caused by implementation specifics of the used H.264 encoder. However, this clearly illustrates unsuitability of H.264 compression for the storage of videos used in NrPPG research.

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REFERENCES

[1] L. A. M. Aarts, V. Jeanne, J. P. Cleary, C. Lieber, J. S. Nelson, S. Bambang Oetomo, and W. Verkruysse. Non-contact heart rate monitoring utilizing camera photoplethysmography in the neonatal intensive care unit — A pilot study. *Early Human Development*, 89(12):943–948, Dec. 2013. 2, 3

[2] J. Allen. Photoplethysmography and its application in clinical physiological measurement. *Physiological Measurement*, 28(3):R1, 2007. 1, 2, 3

[3] F. Andreotti, A. Trumpp, H. Malberg, and S. Zaunseder. Improved heart rate detection for camera-based photoplethysmography by means of Kalman filtering. In *2015 IEEE 35th International Conference on Electronics and Nanotechnology (ELNANO)*, pages 428–433, Apr. 2015. 2

[4] G. Balakrishnan, F. Durand, and J. Guttag. Detecting Pulse from Head Motions in Video. pages 3430–3437, 2013. 5

[5] E. B. Blackford and J. R. Estepp. Effects of frame rate and image resolution on pulse rate measured using multiple camera imaging photoplethysmography. page 94172D, Mar. 2015. 2, 6

[6] R. W. Brown. *Composition of Scientific Words*. Smithsonian Books, Washington, D.C. London, July 2000. 1

[7] A. Buchs, Y. Slovik, M. Rapoport, C. Rosenfeld, B. Khanokh, and M. Nitzan. Right-left correlation of the sympathetically induced fluctuations of photoplethysmographic signal in diabetic and non-diabetic subjects. *Medical and Biological Engineering and Computing*, 43(2):252–257, Apr. 2005. 3

[8] T. J. Cross, M. Keller-Ross, A. Issa, R. Wentz, B. Taylor, and B. Johnson. The Impact of Averaging Window Length on the"Desaturation Indexes during Overnight Pulse Oximetry at High-Altitude". *Sleep*, 38(8):1331–1334, Aug. 2015. 3

[9] J. A. Crowe and D. Damianou. The wavelength dependence of the photoplethysmogram and its implication to pulse oximetry. In *1992 14th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, volume 6, pages 2423–2424, Oct. 1992. 2, 3, 5

[10] W. Cui, L. E. Ostrander, and B. Y. Lee. In vivo reflectance of blood and tissue as a function of light wavelength. *IEEE Transactions on Biomedical Engineering*, 37(6):632–639, June 1990. 2, 3, 5

[11] G. de Haan and A. van Leest. Improved motion robustness of remote-PPG by using the blood volume pulse signature. *Physiological Measurement*, 35(9):1913–1926, Aug. 2014. 2, 3

[12] T. F. o. t. E. S. o. C. t. N. A. S. o. P. Electrophysiology. Heart Rate Variability: Standards of Measurement, Physiological Interpretation, and Clinical Use. *Circulation*, 93(5):1043–1065, Mar. 1996. 3

[13] J. R. Estepp, E. B. Blackford, and C. M. Meier. Recovering pulse rate during motion artifact with a multi-imager array for non-contact imaging photoplethysmography. In *2014 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*, pages 1462–1469, Oct. 2014. 2

[14] B. A. Fallow, T. Tarumi, and H. Tanaka. Influence of skin type and wavelength on light wave reflectance. *Journal of Clinical Monitoring and Computing*, 27(3):313–317, June 2013. 2, 3, 5

[15] T. B. Fitzpatrick. The validity and practicality of sun-reactive skin types I through VI. *Archives of Dermatology*, 124(6):869–871, June 1988. 3

[16] M. v. Gastel, S. Stuijk, and G. d. Haan. Motion Robust Remote-PPG in Infrared. *IEEE Transactions on Biomedical Engineering*, 62(5):1425–1433, May 2015. 3

[17] G. d. Haan and V. Jeanne. Robust Pulse Rate From Chrominance-Based rPPG. *IEEE Transactions on Biomedical Engineering*, 60(10):2878–2886, Oct. 2013. 2, 5

[18] M. A. Haque, K. Nasrollahi, and T. B. Moeslund. Estimation of Heartbeat Peak Locations and Heartbeat Rate from Facial Video. In *Image Analysis*, Lecture Notes in Computer Science, pages 269–281. Springer, Cham, June 2017. 5

[19] M. A. Hassan, A. S. Malik, D. Fofi, N. Saad, B. Karasfi, Y. S. Ali, and F. Meriaudeau. Heart rate estimation using facial video: A review. *Biomedical Signal Processing and Control*, 38:346–360, Sept. 2017. 2

[20] A. B. Hertzman and C. R. Spealman. Observations on the finger volume pulse recorded photoelectrically. *American Journal of Physiology*, (119):334–335, 1937. 1

[21] B. D. Holton, K. Mannapperuma, P. J. Lesniewski, and J. C. Thomas. Signal recovery in imaging photoplethysmography. *Physiological Measurement*, 34(11):1499, 2013. 2, 3

[22] Y. Hsu, Y. L. Lin, and W. Hsu. Learning-based heart rate detection from remote photoplethysmography features. In *2014 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, pages 4433–4437, May 2014. 4

[23] A. Huch, R. Huch, V. König, M. Neuman, D. Parker, J. Yount, and D. Lübbers. Limitations of pulse oximetry. *The Lancet*, 1:357–358, 1988. 3

[24] M. Hülsbusch. *An image-based functional method for opto-electronic detection of skin-perfusion*. Phd thesis, RWTH Aachen dept. of EE.,

2008. 2, 5
[25] L. Iozzia, L. Cerina, and L. Mainardi. Relationships between heart-rate variability and pulse-rate variability obtained from video-PPG signal using ZCA. *Physiological Measurement*, 37(11):1934, 2016. 1, 2, 3
[26] A. A. Kamshilin, O. V. Mamontov, V. T. Koval, G. A. Zayats, and R. V. Romashko. Influence of a skin status on the light interaction with dermis. *Biomedical Optics Express*, 6(11):4326–4334, 2015. 4
[27] A. A. Kamshilin, E. Nippolainen, I. S. Sidorov, P. V. Vasilev, N. P. Erofeev, N. P. Podolian, and R. V. Romashko. A new look at the essence of the imaging photoplethysmography. *Scientific Reports*, 5, May 2015. 1, 5
[28] A. A. Kamshilin, I. S. Sidorov, L. Babayan, M. A. Volynsky, R. Giniatullin, and O. V. Mamontov. Accurate measurement of the pulse wave delay with imaging photoplethysmography. *Biomedical Optics Express*, 7(12):5138–5147, Dec. 2016. 4
[29] M. Kumar, A. Veeraraghavan, and A. Sabharwal. DistancePPG: Robust non-contact vital signs monitoring using a camera. *Biomedical Optics Express*, 6(5):1565–1588, May 2015. 2, 3
[30] J. Lee, K. Matsumura, K.-i. Yamakoshi, P. Rolfe, S. Tanaka, and T. Yamakoshi. Comparison between red, green and blue light reflection photoplethysmography for heart rate monitoring during motion. *Conference proceedings: ... Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Annual Conference*, 2013:1724–1727, 2013. 2, 3, 5
[31] H. Liu, Y. Wang, and L. Wang. A review of non-contact, low-cost physiological information measurement based on photoplethysmographic imaging. *Conference proceedings: ... Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Annual Conference*, 2012:2088–2091, 2012. 2
[32] L. F. C. Martinez, G. Paez, and M. Strojnik. Optimal wavelength selection for noncontact reflection photoplethysmography. volume 8011, page 801191. International Society for Optics and Photonics, Nov. 2011. 2, 3, 5
[33] D. McDuff, S. Gontarek, and R. W. Picard. Improvements in Remote Cardiopulmonary Measurement Using a Five Band Digital Camera. *IEEE Transactions on Biomedical Engineering*, 61(10):2593–2601, Oct. 2014. 3, 5
[34] D. McDuff, S. Gontarek, and R. W. Picard. Remote Detection of Photoplethysmographic Systolic and Diastolic Peaks Using a Digital Camera. *IEEE Transactions on Biomedical Engineering*, 61(12):2948–2954, Dec. 2014. 3
[35] D. J. McDuff, E. B. Blackford, and J. R. Estepp. The Impact of Video Compression on Remote Cardiac Pulse Measurement Using Imaging Photoplethysmography. In *2017 12th IEEE International Conference on Automatic Face Gesture Recognition (FG 2017)*, pages 63–70, May 2017. 4
[36] D. J. Meredith, D. Clifton, P. Charlton, J. Brooks, C. W. Pugh, and L. Tarassenko. Photoplethysmographic derivation of respiratory rate: a review of relevant physiology. *Journal of Medical Engineering & Technology*, 36(1):1–7, Jan. 2012. 1
[37] H. Molitor and M. Kniazuk. A New Bloodless Method for Continuous Recording of Peripheral Circulatory Changes. *Journal of Pharmacology and Experimental Therapeutics*, 57(1):6–18, May 1936. 1
[38] J. Moreno, J. Ramos-Castro, J. Movellan, E. Parrado, G. Rodas, and L. Capdevila. Facial Video-Based Photoplethysmography to Detect HRV at Rest. *International Journal of Sports Medicine*, 36(6):474–480, June 2015. 3
[39] A. V. Moço, S. Stuijk, and G. de Haan. Motion robust PPG-imaging through color channel mapping. *Biomedical Optics Express*, 7(5):1737–1754, Apr. 2016. 3
[40] A. V. Moço, S. Stuijk, and G. d. Haan. Ballistocardiographic Artifacts in PPG Imaging. *IEEE Transactions on Biomedical Engineering*, 63(9):1804–1811, Sept. 2016. 2, 3, 4, 5
[41] N. Nesseler, J.-V. Frénel, Y. Launey, J. Morcet, Y. Mallédant, and P. Seguin. Pulse oximetry and high-dose vasopressors: a comparison between forehead reflectance and finger transmission sensors. *Intensive Care Medicine*, 38(10):1718–1722, Oct. 2012. 3
[42] M. Nitzan, B. Khanokh, and Y. Slovik. The difference in pulse transit time to the toe and finger measured by photoplethysmography. *Physiological Measurement*, 23(1):85–93, Feb. 2002. 3
[43] L.-M. Po, L. Feng, Y. Li, X. Xu, T. C.-H. Cheung, and K.-W. Cheung. Block-based adaptive ROI for remote photoplethysmography. *Multimedia Tools and Applications*, pages 1–27, Mar. 2017. 3
[44] M. Z. Poh, D. J. McDuff, and R. W. Picard. Advancements in Noncontact, Multiparameter Physiological Measurements Using a Webcam. *IEEE Transactions on Biomedical Engineering*, 58(1):7–11, 2011. 3
[45] H. Pälve. Reflection and transmission pulse oximetry during compromised peripheral perfusion. *Journal of Clinical Monitoring*, 8(1):12–15, Jan. 1992. 3
[46] U. Rubins, V. Upmalis, O. Rubenis, D. Jakovels, and J. Spigulis. Real-Time Photoplethysmography Imaging System. In *15th Nordic-Baltic Conference on Biomedical Engineering and Medical Physics (NBC 2011)*, IFMBE Proceedings, pages 183–186. Springer, Berlin, Heidelberg, 2011. DOI: 10.1007/978-3-642-21683-1_46. 4
[47] A. Schäfer and J. Vagedes. How accurate is pulse rate variability as an estimate of heart rate variability?: A review on studies comparing photoplethysmographic technology with an electrocardiogram. *International Journal of Cardiology*, 166(1):15–29, June 2013. 2, 3
[48] C. G. Scully, J. Lee, J. Meyer, A. M. Gorbach, D. Granquist-Fraser, Y. Mendelson, and K. H. Chon. Physiological Parameter Monitoring from Optical Recordings With a Mobile Phone. *IEEE Transactions on Biomedical Engineering*, 59(2):303–306, Feb. 2012. 3
[49] R. Stricker, S. Müller, and H. M. Gross. Non-contact video-based pulse rate measurement on a mobile service robot. In *The 23rd IEEE International Symposium on Robot and Human Interactive Communication*, pages 1056–1062, Aug. 2014. 3
[50] Y. Sun, S. Hu, V. Azorin-Peris, R. Kalawsky, and S. Greenwald. Noncontact imaging photoplethysmography to effectively access pulse rate variability. *Journal of Biomedical Optics*, 18(6):061205, June 2013. 3
[51] Y. Sun and N. Thakor. Photoplethysmography Revisited: From Contact to Noncontact, From Point to Imaging. *IEEE Transactions on Biomedical Engineering*, 63(3):463–477, Mar. 2016. 1, 2, 3, 4
[52] C. Takano and Y. Ohta. Heart rate measurement based on a time-lapse image. *Medical Engineering & Physics*, 29(8):853–857, Oct. 2007. 3
[53] L. Tarassenko, M. Villarroel, A. Guazzi, J. Jorge, D. A. Clifton, and C. Pugh. Non-contact video-based vital sign monitoring using ambient light and auto-regressive models. *Physiological Measurement*, 35(5):807–831, May 2014. 2, 3
[54] X. F. Teng and Y. T. Zhang. The effect of contacting force on photoplethysmographic signals. *Physiological Measurement*, 25(5):1323–1335, Oct. 2004. 3
[55] N. S. Trivedi, A. F. Ghouri, N. K. Shah, E. Lai, and S. J. Barker. Effects of motion, ambient light, and hypoperfusion on pulse oximeter function. *Journal of Clinical Anesthesia*, 9(3):179–183, May 1997. 3
[56] M. van Gastel, S. Stuijk, and G. de Haan. Motion Robust Remote-PPG in Infrared. *IEEE transactions on bio-medical engineering*, 62(5):1425–1433, May 2015. 3
[57] W. Verkruysse, L. O. Svaasand, and J. S. Nelson. Remote plethysmographic imaging using ambient light. *Optics express*, 16(26):21434–21445, Dec. 2008. 2
[58] M. Villarroel, A. Guazzi, J. Jorge, S. Davis, P. Watkinson, G. Green, A. Shenvi, K. McCormick, and L. Tarassenko. Continuous non-contact vital sign monitoring in neonatal intensive care unit. *Healthcare Technology Letters*, 1(3):87–91, Sept. 2014. 3
[59] W. Wang, A. C. d. Brinker, S. Stuijk, and G. d. Haan. Robust heart rate from fitness videos. *Physiological Measurement*, 38(6):1023, 2017. 5
[60] W. Wang, S. Stuijk, and G. d. Haan. Exploiting Spatial Redundancy of Image Sensor for Motion Robust rPPG. *IEEE Transactions on Biomedical Engineering*, 62(2):415–425, Feb. 2015. 3
[61] D. B. Wax, P. Rubin, and S. Neustein. A comparison of transmittance and reflectance pulse oximetry during vascular surgery. *Anesthesia and Analgesia*, 109(6):1847–1849, Dec. 2009. 3
[62] T. Wu, V. Blazek, and H. J. Schmitt. Photoplethysmography imaging: a new noninvasive and noncontact method for mapping of the dermal perfusion changes. volume 4163, pages 62–71. International Society for Optics and Photonics, Nov. 2000. 2
[63] S. Xu, L. Sun, and G. K. Rohde. Robust efficient estimation of heart rate pulse from video. *Biomedical Optics Express*, 5(4):1124–1135, Mar. 2014. 3, 4
[64] Y.-P. Yu, P. Raveendran, and C.-L. Lim. Dynamic heart rate measurements from video sequences. *Biomedical Optics Express*, 6(7):2466–2480, June 2015. 4
[65] H. Zhu, Y. Zhao, and L. Dong. Non-contact detection of cardiac rate based on visible light imaging device. volume 8498, page 849806. International Society for Optics and Photonics, Oct. 2012. 2