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Non-contact heart rate monitoring utilizing camera photoplethysmography in the neonatal intensive care unit — A pilot study

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a b s t r a c t

Background: Presently the heart rate is monitored in the Neonatal Intensive Care Unit with contact sensors: electrocardiogram or pulse oximetry. These techniques can cause injuries and infections, particularly in very premature infants with fragile skin. Camera based plethysmography was recently demonstrated in adults as a contactless method to determine heart rate.
Aim: To investigate the feasibility of this technique for NICU patients and identify challenging conditions. Study design and participants: Video recordings using only ambient light were made of 19 infants at two NICUs in California and The Netherlands. Heart rate can be derived from these recordings because each cardiovascular pulse wave induces minute pulsatile skin color changes, invisible to the eye but measurable with a camera.
Results: In all infants the heart beat induced photoplethysmographic signal was strong enough to be measured. Low ambient light level and infant motion prevented successful measurement from time to time.
Conclusions: Contactless heart rate monitoring by means of a camera using ambient light was demonstrated for the first time in the NICU population and appears feasible. Better hardware and improved algorithms are required to increase robustness.

1. Introduction

The heart rate (HR) is a critical parameter to assess the well-being of infants in the neonatal intensive care unit (NICU). Episodes of bradycardia occur frequently in premature infants due to a variety of causes, including immature respiratory development or sepsis [1,2]. Current HR monitoring techniques include electrocardiography (ECG) and pulse oximetry based on photoplethysmography (PPG) [3]. These techniques are reliable and inexpensive. However, there are several disadvantages because both are contact devices using adhesive sensors. Placement and removal of the sensors and the attachment to wires cause discomfort, stress, pain and sometimes even epidermal stripping. The latter occurs particularly in infants b 27 weeks of gestational age, because in these infants the bond between the sensor and dermis is stronger than the epidermal–dermal junction [4–6]. The patches and wires appear on X-rays and complicate reading the film. Furthermore, the obtrusive- ness of the wires impairs parent–child bonding, especially during kangaroo mother care. Anand and Scalzo suggested that pain, stress

and maternal separation of NICU patients have a negative impact on cognitive development [7]. In addition, a study by Chen et al indicates that repetitive application and removal of patches, adversely affect the infant's well-being and developmental outcome [8]. In view of the above, a contactless HR monitoring technique would be highly desirable. Recently, camera based PPG was demonstrated [9–17]. This novel technique is entirely contactless but uses the same principle as con- tact PPG, better known as pulse-oximetry. Blood absorbs light more than surrounding tissue so variations in blood volume affect light transmission and reflectance. While contact PPG predominantly uses transmissive mode, camera PPG is typically performed in reflective mode. The cardiovascular pulse waves cause changes in the volume of arterioles which result in minute pulsatile skin color changes. These color changes may be compared to blushing (more blood, red- der skin), except that they are less intense. While invisible to the eye, these 'micro-blushes' can be detected with a camera.

The aim of this pilot study is to investigate the feasibility of camera based PPG for contactless HR monitoring in newborn infants in the NICU with ambient light. We did not use dedicated illumination as it might hinder the infant and would increase the experimental footprint in the NICU.

2. Methods

2.1. Study design

Infants were studied in the NICU in both the Children's Hospital of Orange County (CHOC), California, USA and in the Máxima Medical Center (MMC), The Netherlands. Institutional Review Board approval (CHOC#090768 and UCI#2009-7046, clinicaltrials.gov: NCT00989859, Philips Research-MMC #2010-075) and informed parental consent were obtained prior to measurements. Since the objective was to explore potential challenging conditions of the technique no exclusion criteria were defined and any infant in the NICU met the inclusion criteria.

2.2. Experimental setup

A photograph of the experimental setup is shown in Fig. 1A. A standard color digital camera (uEye, IDS imaging, Obersulm, 300 × 300 pixels, 15 or 30 frames/s, 8 bit) was used in combination with an objective lens (Computar, 35 mm, f/1.3). The camera was placed on a tripod at approximately 1 m distance from the infant. Recordings (1–5 min) of the infant were taken either through the plexiglass or directly with open incubators. The study was designed such that the infants were never touched or repositioned for study purposes and hospital workflow always took priority over the recordings. No dedicated illumination was used in any of the measurements. Ambient light level in the NICU was measured by a Sekonic light meter (L758DR, Elmsford NY). The camera was aimed at uncovered body parts (e.g., head, arm, and thorax). Movies were saved in uncompressed AVI format by the camera and transferred to a PC. Reference HR was obtained through either ECG sensors (Red Dot 2282E, 3M Healthcare, or Blue Sensor NEOX from Ambu A/S for premature infants weighing b 1 kg and N 1 kg, respectively) and/or pulse oximetry sensors (Masimo SET, M-LNCS Inf).

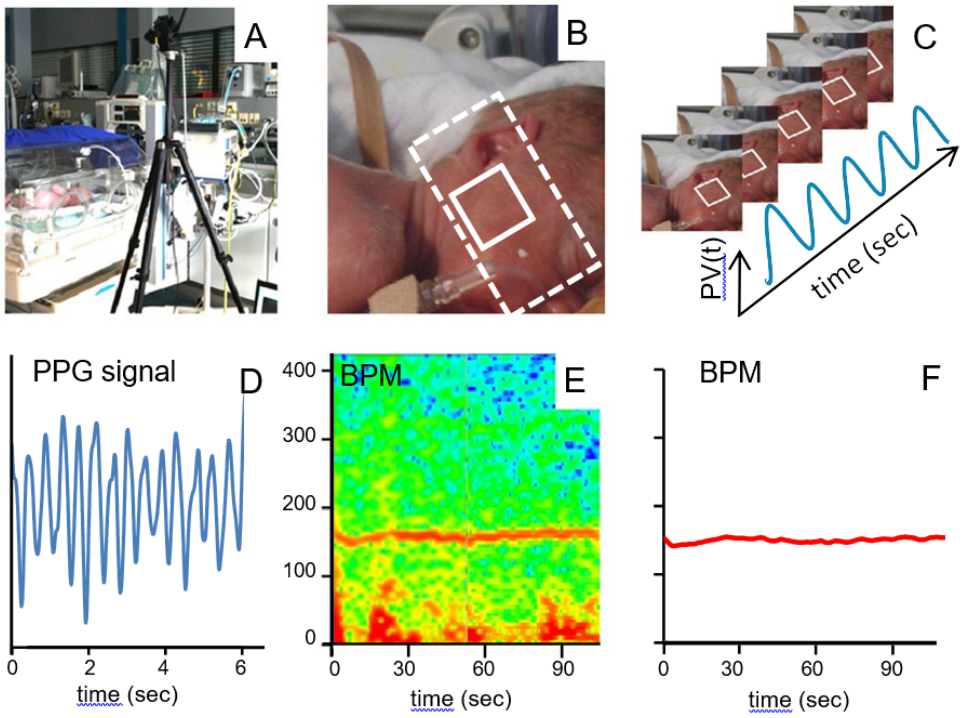

Fig. 1. Method for HR detection. Photograph of the experimental setup (A). Regions of interest ROIm and ROIs (dashed and solid lines in (B), respectively) were manually selected in a video frame using a graphical user interface. After correction for motion using ROIm, color variations in ROIs are calculated from pixel values for each frame to obtain a plethysmogram (C–D). Fourier analysis is performed on this signal in a moving window of 7 s resulting in a JTFD (E). The dominant frequency is then plotted in time and represents the HR (F).

2.3. Image and signal processing

By means of a graphical user interface (Matlab, Mathworks, Natick, MA) a first region of interest (ROIm) was manually selected in a video frame (Fig. 1B) to be used as a template for global motion tracking of the infant (IMAQ 3 match pattern, National Instruments, Austin, TX). This motion tracking ROI was selected to have contrast in it (e.g. an eye, or patch) to improve the motion tracking accuracy. Within ROIm a second, smaller ROIs containing merely skin was selected. For each frame in ROIs, the average pixel value (PV) was calculated (Fig. 1C). Plot- ting PV of ROIs for each frame yields a PV(t) signal (Fig. 1D). We analyzed the green channel because the PPG signal is strongest at this color [12]. Variations in PV(t) of the ROIs as a function of time are caused by minute color changes in the skin. These result from the cardiovascular pulse wave traveling through the cutaneous blood vessels. The PV(t) signal for the red channel (where the variation in reflectance is known to be very small [18]) was used to correct the green PPG signal for illumination intensity changes. For medical purposes, Shelley et al. proposed to visualize plethysmograms as joint-time-frequency dia- grams (JTFDs) [19]. Fig. 1E shows a JTFD where the red band clearly indicates the HR as a function of time, matching the reference HR trace (Fig. 1F).

3. Results

A total of 19 infants with gestational ages ranging from 25 to 42 weeks, postnatal ages ranging from 3 days to 4 weeks, and weights from 470 to 3810 g were studied. Two were ventilated, one of which with HFOV. One infant had sepsis. No inotropics had been administered to the infants at the time of the measurement. Ambient light levels in the NICU varied from 20 to 180 lx. For comparison, typical office work floor light intensities range from 400 to 750 lx. During phototherapy to treat neonatal hyperbilirubinemia the light level spot measurements were much higher (up to 8000 lx). In both NICUs the illumination sources were daylight (through windows) or ceiling mounted fluorescent lights.

In all infants we were able to extract HR from the camera based PPG signal, but noise, caused by infant motion and/or low or fluctuating light levels, often disrupted continuous HR measurement. A significant difference between the HR of the camera and the control HR (ECG or pulse- oximetry) was never observed; poor results were always caused by loss of signal or too low resolution of the PPG images. The overall results are listed in Table 2. We categorized our results as poor, medium and good signals. A poor result is defined as a HR matching control in b 50% of the total recording time, a medium signal as a HR matching control in 50 up to 90% of time and a good result as a HR matching control in N 90% of time. Matching was defined as BPM difference ≤ 5. No difference was found between the results of CHOC and the MMC (Table 1).

Table 1
List of abbreviations.

Abbreviation	Full definition
HR	Heart rate
NICU	Neonatal intensive care unit
ECG	Electrocardiogram
PPG	Photoplethysmography
CHOC	Children's Hospital of Orange County
MMC	Máxima Medical Center
AVI	Audio video interleave
PC	Personal computer
ROI	Region of interest
PV	Pixel value
JFTD	Joint time frequency diagram
HFOV	High frequency oscillation ventilation
BPM	Beats per minute
SNR	Signal to noise ratio
SSSS	Staphylococcal scalded skin syndrome

Table 2
Overall results of HR measured with a camera.

	Poor signal[a]	Medium signal[b]	Good signal[c]	Total infants
	n	*n*	*n*	*n*
CHOC	0	2	7	9
MMC	1	3	6	10
Total	1	5	13	19

[a] Poor signal: a HR matching control b50% of the time.
[b] Medium: a HR matching control in 50 up to 90% of the time.
[c] Good signal: a HR matching control N90% of the time.

In Fig. 2, camera based HR monitoring is compared to those from ECG and pulse-oximeter. The subject was an infant of 36 weeks gestational age weighing 1980 g. Ambient light level during recording was 150 lx. The JTFD (Fig. 2A) features a band around 160 beats per minute (BPM). This band visualizes the camera based HR trace and corresponds well with the reference HR traces from the ECG and contact pulse oximeter (Fig. 2B) albeit that there are minor discrepancies, typically smaller than 5 BPM) The broader bands between t = 0.3 and 2.6 min and t = 4 to 5.2 min in Fig. 2A correspond to strong disruptions of the PPG signal, caused by the infant squirming; the algorithm (see section on image and signal processing) failed to completely remove the resulting disturbances in the PV(t) signal.

Bland–Altman analysis of HR from camera and ECG did not reveal a relevant bias nor trend (Fig. 2C), validating that the camera method indeed measures HR. In addition, we include a Bland–Altman plot for HR from two conventional devices: a pulse-oximeter and ECG (Fig. 2D). The discrepancies between camera derived HR and ECG (Fig. 2C) are even slightly smaller than for the two conventional techniques (Fig. 2D). The apparent downward trend in Fig. 2D is very weak (R2 = 0.2307) and coincidentally caused by small time segments with relatively large discrepancies, occurring at different HRs in this particular 5 minute trace. The pulse-oximeter HR happened to be lower at relatively high BPM (indicated by '<' in figure B), and vice versa ('>'). Please note that due to integer representation of the HR in both ECG and pulse oximeter many points (300, one per second) are overlapping, dramatizing the visual trend.

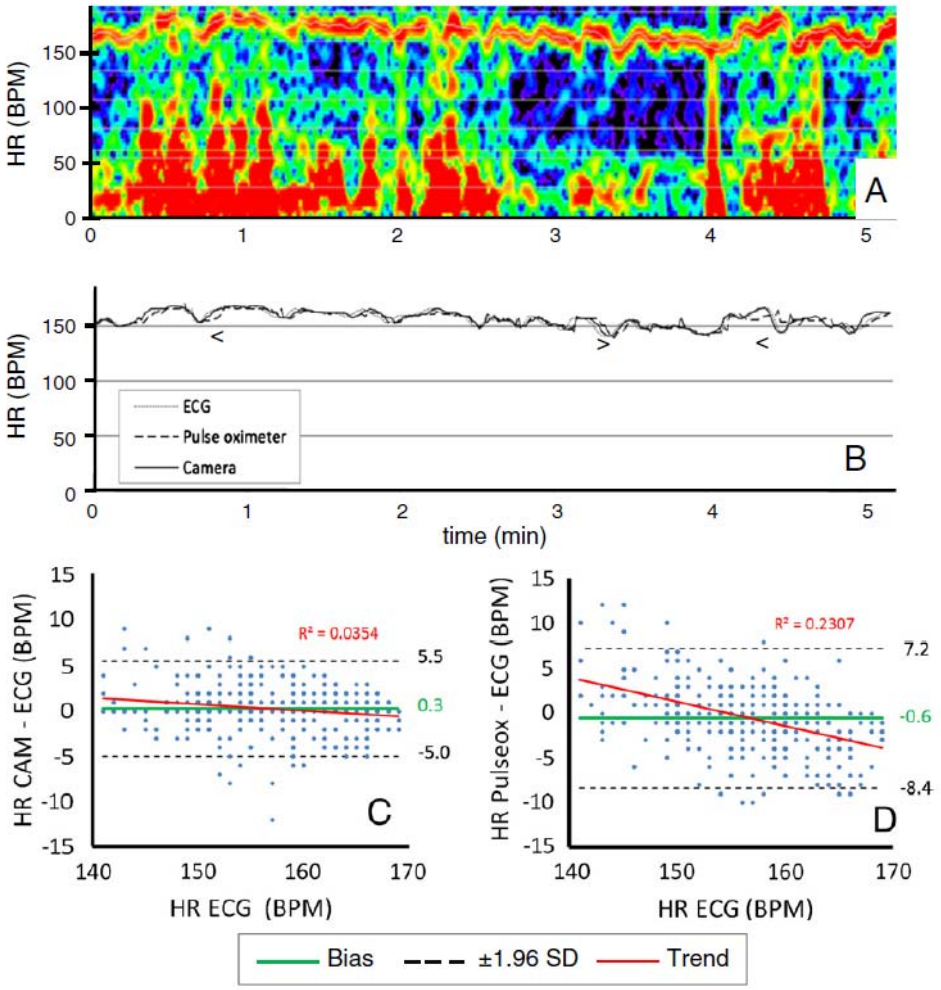

Fig. 2. Camera based HR (represented as JTFD in A) is compared with HR traces of ECG and contact pulse oximeter (B–D). The broader bands between t = 0.3 and 2.6 min and t = 4 to 5.2 min in Fig. 2A correspond to strong disruptions of the PPG signal, caused by the infant squirming. Bland–Altman plots for camera vs ECG (C) and pulse oximeter vs ECG (D).

In the nineteen studied cases several potentially challenging conditions relevant for clinical practice were encountered and are highlighted below; rocking motion during kangaroo mother care, high frequency oscillation ventilation (HFOV), dark skin, phototherapy and affected skin. First, an infant was monitored on the lap of the mother (Fig. 3A) while she was gently rocking (Movie1.avi). Despite this considerable motion, with excursions of approximately 5 cm at a rocking frequency of about 1 Hz, the infant's HR could be monitored on the forehead (Fig. 3B) which matched the control HR (Fig. 3C). Second, an infant on HFOV was recorded. The HR could still be monitored at approximately 170 BPM (~3 Hz) despite the physical oscillation of the infant by the HFOV at 8 Hz. Third an infant with dark skin of Hispanic origin (Fitzpatrick scale V) was monitored. While the signal strength was relatively small the HR could still be observed in the JTFD. Fourth, phototherapy (PT-4000, Dräger Medical Inc.,Telford, PA) to treat hyperbilirubinemia did not impede camera based HR monitoring (Fig. 4A). On

the contrary, the noise level was markedly lower due to the better illumination level up to 8000 lx. This signal had by far the best SNR in our study and the camera derived HR correlated perfectly with the ECG derived HR. For comparison, in Fig. 4B we show the JTFD for the worst SNR in our study, which was recorded under very poor illumination conditions of 19 lx.

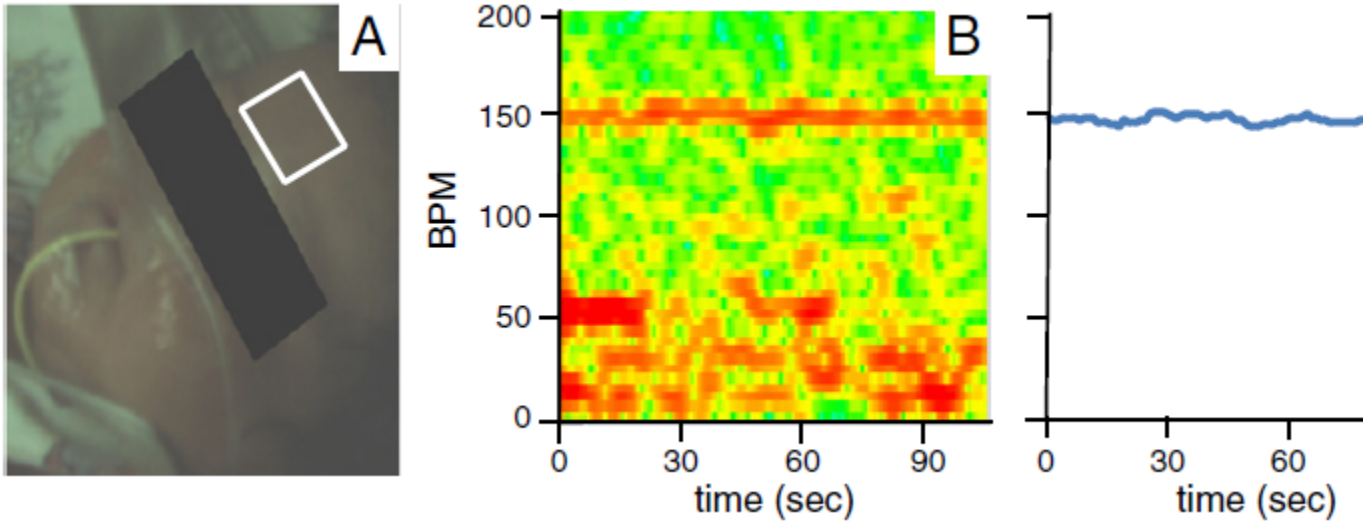

Fig. 3. HR monitoring during kangaroo mother care. Video still of the infant with the ROI selected on the forehead (A). JTFD of the camera based HR (B). Reference HR derived from ECG (C).

Fifth, an infant with skin affected by Staphylococcal Scalded Skin Syndrome (SSSS) was recorded. The infection started at the umbilicus and progressed radially (Fig. 5A). To analyze potential PPG amplitude differences between unaffected, recently affected and the skin where the infection originated (areas I, II and III respectively in Fig. 5B), we defined three ROI's to generate three PPG signals. Since JTFD representation is not preferred to highlight amplitude differences we plot them as the original temporal signals. In all three areas, the HR could be monitored. The PPG signal amplitudes in the affected skin area (I–II) were larger than in the unaffected skin area (III) (Fig. 5C).

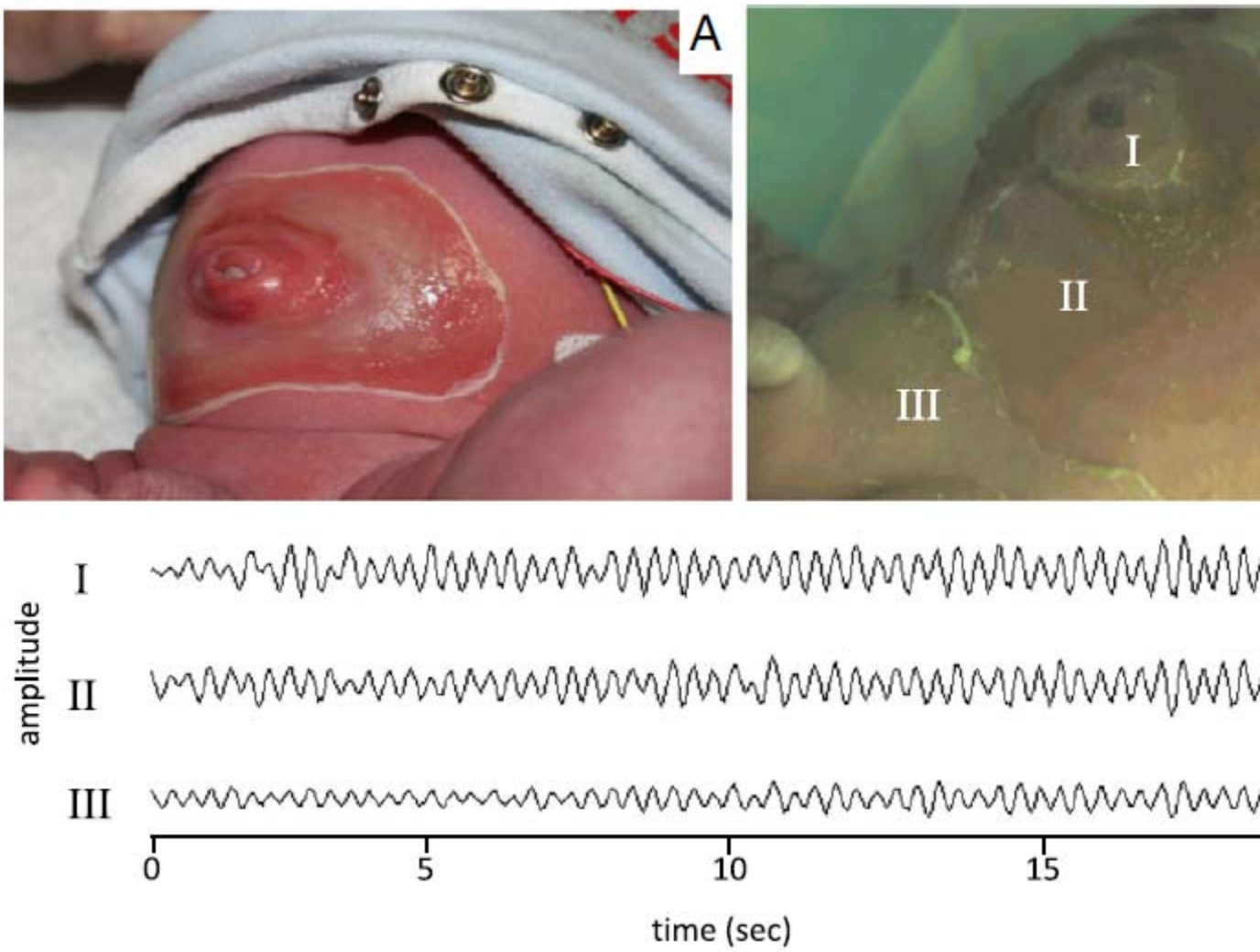

Fig. 5. Photograph of the affected abdomen in a term infant with SSSS (A). Video still of the affected abdomen, 18 h after the photograph was taken (B). Areas I, II and III in B, indicate the origin of the infection (umbilicus), later infected peri-umbilical skin and unaffected skin in the pubic area, respectively. Temporal signals for these areas illustrating the differential amplitudes
(C).

4. Discussion

The most fundamental condition for camera based PPG to be feasible in the NICU is that the cardiovascular induced PPG signal has to be detectable in the infants at an arbitrary anatomical location. This means that non-cardiovascular related changes in skin optical reflectivity (such as caused by redistribution of venous blood, e.g. during sepsis or by repositioning a limb causing changes in hydrostatic pressure) have to be smaller than those induced by the cardiovascular pulse wave. We could identify the HR related PPG signal in all nineteen infants albeit not continuously. While nineteen is a small number,

the overall results suggest that the fundamental condition for feasibility of this technique is met for the general NICU population. We realize that not all challenging conditions could be investigated in this limited study, however, the ones we did encounter provide useful insights for camera PPG and will be addressed in the next paragraph.

The conditions that frequently prevented continuous HR measurement are infant motion and poor illumination conditions. Infant motion often disturbed the PPG signals, but not necessarily. In the case of the gentle rocking during kangaroo care (Fig. 3 and Movie1.avi) where the orientation of the monitored skin area with respect to the camera and illumination sources remained relatively constant, simple motion tracking algorithms (IMAQ match pattern 2, LabView, National Instruments) are sufficient to provide continuous HR monitoring. Despite the rocking motion during the first 20 s of the recordings a strong HR signal was retrieved and matched the reference HR. Rotational motion such as the squirming infant (Fig. 2), however, often caused a different light source to become the dominant illumination for the observed skin area; e.g. natural vs. artificial light. Although our HR extraction algorithms aim to account for this, it remains a challenge. A more trivial effect of motion was that the monitored skin area was often outside the limited camera's field of view in our experimental setup. It is important to note that artifacts induced by infant motion are common also in contact pulse oximetry and ECG based HR recordings as well and do not significantly hamper the overall clinical utility. In addition to infant motion, poor illumination conditions in the NICU also compromised the PPG signal. The illumination levels were not only low, but also fluctuating due to the fact that light was not diffuse but originating from predominant directions — ceiling spot light or window (daylight). As a result, motion of the infant itself and/or staff passing by caused pronounced shadows which negatively affected the PPG signal to noise ratio (SNR). Of note, during tests on adults, we have observed that our HR algorithms are more robust during overcast days which provide diffuse light and thus less sharp shadows.

For the one infant with dark skin the SNR was lower, but the HR could still be extracted. Theoretically, the SNR of the PPG signal is expected to decrease with increasing pigmentation level as the epidermal melanin absorbs light and reduces the amount of light reaching the deeper pulsatile vessels. At this moment it is impossible to conclude on the feasibility of this technique for all skin types.

HFOV, phototherapy and skin affected by SSSS were not prohibitive at all. HFOV caused a distinct periodic signal, but it did not interfere with camera based PPG since it was at a higher frequency (8 Hz) than the infant's HR (b3 Hz). We initially considered phototherapy for jaundice as a potential challenge because the light source might contain a 60 Hz intensity modulation of the AC power supply and interfere (aliasing) with the camera frame rate of 15 or 30 Hz. Moreover, the light emitted by this phototherapy device is predominantly blue while the PPG signal is known to be strongest at the green channel [12]. However, no such effects were observed. In fact, the overall higher light intensity – including that of green light – benefited the quality of the PPG signal considerably. For the infant with SSSS, the PPG signal was even stronger in affected skin than in adjacent healthy skin. Whitish colored skin that had been affected for two days and appeared less perfused (area I) showed a significantly stronger signal than did healthy skin (area III), perhaps indicating increased perfusion during wound healing.

Successful introduction of camera PPG in the NICU would require increased robustness of HR monitoring, but also be capable of robust monitoring of respiration rate and SpO2.We believe that a satisfactory robustness can be achieved by using a combination of improved algorithms, more sensitive cameras and dedicated illumination to compensate for infant motion and suboptimal illumination conditions. It would be elegant, however, to use ambient light instead of dedicated illumination because it is in line with the unobtrusive, passive nature of this camera based technique. Monitoring of the respiration rate is possible, as we showed in a poster presentation at the 2011 PAS/ASPR convention (Denver, CO) [20], while SpO_2 is much more challenging. [9,11].

We believe that camera PPG technology is in its infancy and that much work needs to be done to make it work but also that the benefits for premature infants justify efforts towards this goal. Especially in view of the increasing survival rate of premature infants and the trend to resuscitate at younger gestational ages the need for an alternative, non-contact method is becoming increasingly urgent [21]. To the best of our knowledge this is the first study demonstrating noncontact, camera based HR monitoring in newborn infants in the NICU using only ambient light.

Conflict of interest statement

The authors have no conflict of interest to declare.

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