Towards Continuous Monitoring of Pulse Rate in Neonatal Intensive Care Unit with a Webcam

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***Abstract*— we describe a novel method to monitor pulse rate (PR) on a continuous basis of patients in a neonatal intensive care unit (NICU) using videos taken from a high definition (HD) webcam. We describe algorithms that determine PR from videoplethysmographic (VPG) signals extracted from multiple regions of interest (ROI) simultaneously available within the field of view of the camera where cardiac signal is registered. We detect motion from video images and compensate for motion artifacts from each ROI. Preliminary clinical results are presented on 8 neonates each with 30 minutes of uninterrupted video. Comparisons to hospital equipment indicate that the proposed technology can meet medical industry standards and give improved patient comfort and ease of use for practitioners when instrumented with proper hardware.**

I. Background and Introduction

Contact devices used for monitoring pulse rate (PR) for a prolonged duration may increase the risk of infections or hospital acquired pressure ulcers (HAPUs) in critically ill patients, in particular infants [1]. Medical device that initially fits properly may exert pressure to the skin over time resulting in tissue compression and vascular insufficiency to the region. Emotional suffering, discomfort, irritation, soreness are yet other factors to consider, especially in neonates/infants since they have limited capacity to communicate discomfort other than by crying. A non-contact sensing system that is accurate can not only greatly improve the comfort of patients for long period of observation/monitoring by providing infection/pain free measurements, but also has potential applications for remote healthcare for episodic/continuous monitoring at homes, clinics in rural villages and locations that may be far from a specialist.

A non-contact monitoring of neonatal respiration rate (RR) based on infrared thermography is described in [2,3]. Pulsatile blood flow modulates skin temperature because of heat exchange between vessels and surrounding tissue. Contact-free measurement of cardiac pulse based on measurements of modulations in skin temperature was documented in Ref. [4]. In 1997, Greneker obtained [5] the first contact-free PR and RR measurements at a distance of 30 feet without any physical connection to the subject based on radar. Refs. [6-8] documented additional prototypes based on similar principles. Magnetic induction measurement technique is another approach proposed in Ref. [9] for monitoring heart and lung activity.

Photoplethysmography (PPG) is an optical measurement technique that can be used to detect blood volume change in the vascular bed of a selected skin area [10]. The basic concept of videoplethysmography (VPG) is similar to backscattered reflectance PPG, in which a light source illuminates an exposed skin area, and the reflected light is measured with a photodetector array inside a camera. As light enters the tissue, it is reflected by deep structures depending on the wavelength, but is attenuated mainly by light absorbing hemoglobin in superficial blood vessels. The variation of blood volume overtime due to pulsation is registered as subtle color change in each pixel. Normally, ROI covering a large exposed skin area is used to integrate the color variations.

The work on color-based non-contact video monitoring of RR and PR with a digital camera was developed by numerous authors [11-25]. Verkruysse et al [12] showed that the green channel of the RGB signal under ambient illumination features the strongest PPG signal because it corresponds to the absorption peak of ambient light by hemoglobin. The work described by Poh et al. and Tsouri et al [14,18] improved the performance of such methods by applying blind and constrained source separation using independent component analysis. Furthermore, Yu Sun et al published research papers [16,17,23] for motion compensated non-contact imaging. Zhao et al demonstrated non-contact measurements of PR and RR for both day and night conditions on (i) a 30 second video of a one-month old infant while the baby is sleeping, (ii) a mouse at rest over a period of 10 seconds, (iii) an adult zebra fish, (iv) a pig, and (v) an adult human.

As described above, while many researchers have applied contact-free video-based method to detect PR, to the best of our knowledge, none has demonstrated capabilities of monitoring at a distance of 3 feet or higher of neonates in a NICU environment for a prolonged period (>30 minutes). During this long period of observations, there are many challenges to overcome, i.e., infants may not be cooperative and may move around freely in a hospital bed. The types of motion of head and chest are different, i.e., head moves more often than chest and at times they are occluded by arms. The primary idea of this paper is to simultaneously track more than one ROI and fuse decisions based on different

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situations, we will be able to reduce motion errors while measuring PR on a continuous basis.

This paper is organized as follows: Section II provides a brief description of various algorithms including the continuous PR extraction, motion tracking and multiple ROI selection, and decision algorithms; Section III describes the clinical study including patient enrollment and PR tracking results for 30 minutes; we conclude with Section IV.

II. Continuous Pulse Rate Detection Algorithm

A. Continuous PR detection under no motion

A functional block diagram of the continuous cardiac pulse monitoring from video recordings is shown in Fig. 1 [26]. From initial one or a few frames, a ROI is selected and its location is tracked in subsequent frames; pixels from ROI's are spatially averaged to create time-series signals. Batches are created by sliding a window of 15 seconds (i.e., the adopted window length by most medical instruments) with 96.67% overlap between consecutive batches, which means replacing only 1 second of frames from previous batch (Fig. 2) to provide updates every second. Since pulsatile signal are more prominent in the green channel, we chose this channel for further processing. To create continuous pulsatile signal, we need to stitch the extracted pulsatile signal between successive batches. This provides the abilities to construct a stream of pulsatile signal as in a PPG waveform. PR is calculated using spectral density curves obtained from the signal. The basic PR extraction algorithm contains the following key steps:

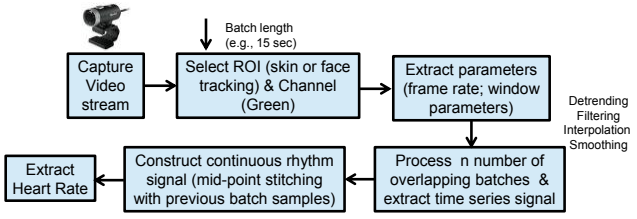

Figure 1: Continuous monitoring of the PR & cardiac pulse

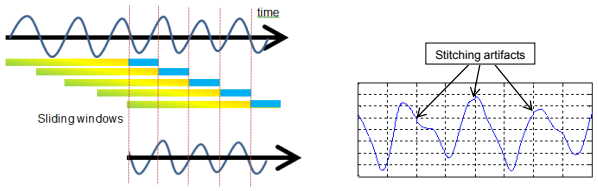

Figure 2: Batch processing with sliding window

De-trending: A slow varying trend in the time-series signal can lead to non-stationary component with undesirable sub-bands. As part of the pre-processing step, the signal is de-trended by a time-varying high pass finite impulse response (FIR) filter to remove very low frequency components.

Band-pass filtering: In this step, prefiltering of the stationary time-series signal is done to retain the cardiac frequencies. The filter will remove undesirable frequencies below and above the expected frequency range. For the subjects tested, we used a wide spectral range from 1.23Hz to 4Hz by a higher order band limited FIR filter.

Interpolation: Cubic interpolation is applied to up-sample the signal to increase the number of data points.

Smoothening: The signal was then smoothened using a digital moving average filter with a suitable moving window to remove artifacts and phase distortions.

Stitching: Stitching any two consecutive overlapping batches by using mid-sections of individual batches as opposed to end-section resulted in continuous cardiac signal.

PR estimation: PR was estimated using the peak frequencies of the spectral density curves operating on individual batch.

B. Continuous PR detection under motion with motion tracking and motion compensation

In Section II (A), we assumed that the subject under monitoring was stationary. However, motion can be a serious issue even in contact based PR measurement systems [27]. In a remote video-based monitoring system, subject movement such as turning the head, moving an arm or leg, and the like, may induce artifacts into the VPG signal. When a neonate is being monitored under a camera, there can be multiple sources of motion including subject motion and motion induced by the environment such as camera or light source motion. Each of these sources of motion can affect the estimated PR. For example, even though camera motion won't change the intrinsic pulsation of the subject, it is the change of acquisition geometry among the ROI, camera and light source, which affect the reflected light from ROI's. Meanwhile, subject motion not only affects the reflected light from the ROI's, but might also change the intrinsic pulsation. In our setup, the camera and light source motions are less of a concern because we used ceiling light as ambient source and the camera was mounted on a fixed pole. Our focus will be on subject motion, which is further separated into two sources: motion originated inside and outside of ROI's.

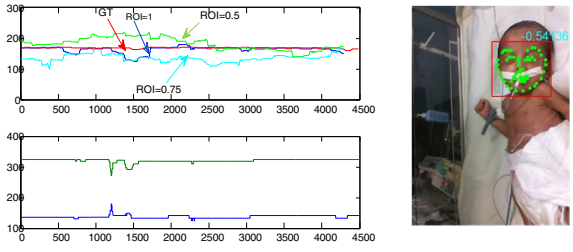

Figure 3: Identified ROI (right), the tracked motion signals (bottom left graph) and the estimated PR (top-left graph) from 3 different sizes of ROI

In a non-contact video-based PR monitoring system, desired ROI's are exposed skin areas such as the face area. ROI's can be selected through a face detection method as shown in [28]. Once the ROI's are identified, their movements are tracked by methods such as [29,30]. The locations (*i.e., x* and *y* coordinates) or orientations and sizes of each ROI's in each frame are recorded as a set of indicators of subject motion. Figure 3 shows an example of this process (except that there wasn't any motion in the scene

besides the identified ROI region), where the top and bottom graphs show the estimated PR with ground truth and the recorded *x* and *y* locations of the ROI that is indicated by the red box in the right picture, respectively.

Motion Compensation: Determining a proper threshold of motion signals is critical. The threshold on the amount of movement will determine whether a time-series segment can be reliably used for PR estimation or not. Once we identify a time-series segment where the movement by the subject is not likely to have induced motion artifacts in the video, VPG signal is extracted from the green channel. It is then analyzed to identify a first frequency of interest. A band-pass filter is created which has a center frequency corresponding to this frequency of interest with a pre-defined bandwidth. Thereafter, the band-pass filter, which was created by having processed the previous batch immediately prior to the current batch, is used to filter the current time-series signal.

C. Multiple Regions of Interest and Decision Algorithms

In a contact-based system, a single sensor could read PR in a small area and if there is motion then the measurements may be corrupted. On the contrary, using a video camera we could make use of several exposed skin regions available within the field of view of the camera, for example face, chest, arms, etc., where PR signals can be registered. Continuous PR monitoring can be improved by selecting and tracking multiple ROIs of skin regions from video frames to generate respective time-series signals, estimate PR from each set of time-series signals, compare these results with PR generated from the previous batch and then chose values closer to the previous PR or fuse them. This assumes that change in PR over a designated time interval (e.g., a second) is small and would be the case if the overlap between successive batches is large. This process repeats for continuous monitoring.

III. CLINICAL STUDY

A. Enrolment of Neonates

Neonates between the gestation periods of 37 weeks to 40 weeks and hemodynamically stable with birth weight ranging from 5.3 pounds to 8 pounds were randomly selected and enrolled for the study after obtaining written consent from one of the parents. Study was approved by the Institutional Ethical Committee affiliated to Manipal University, India.

Preterm infants, neonates requiring ventilator support, and neonates on phototherapy for management of neonatal hyperbilirubinemia were excluded from the study. Neonates were nursed under the thermo-neutral environment using radiant warmer. Temperature of the neonates was maintained between 36 to 36.5 °C through servo controlled mode. Ambient temperature of the neonatal intensive care was maintained between 26 to 28 °C with relative humidity of 65-70% as per standard recommendations. Background lighting of the infant warmer was on. 300 lux of light intensity was recorded using light meter during video capture which is the normal NICU lighting without any additional modifications. Video of the neonates were recorded with image resolution of 640x480 at one hour post feeding state to minimize large subject movements. During the period of continuous video recording, chest electrodes were removed and video was focused on infant's chest and face at a distance of ~3 feet. Simultaneously PR, RR, and oxygen saturation were recorded with IntelliVue MP 20 Philips Neonatal monitors for ground truth data. Videos were sent electronically to Xerox Innovation Group – PARC, for further processing.

B. Results of Tracking PR in Neonates

Bland-Altman analysis on eight different neonates, each 30 minutes long is summarized in Table I below.

Table I: The mean bias with 95% limits of agreement, maximum change in reference beat-to-beat rate and the percentage of video segments lost via motion isolation for each subject.

#	Mean bias ($\bar{d}$) (in bpm)	95% limits of agreement [1.96*SD] (in bpm)	Maximum change in reference beat-to-beat	% loss of data via motion isolation
1	1.88	4.12	10	16.7
2	1.86	2.69	2	2.9
3	0.62	1.04	2	0.8
4	5.03	11.56	26	21.5
5	1.92	3.92	8	7.7
6	5.00	13.91	24	24.5
7	2.66	4.76	4	8.9
8	1.19	1.89	3	0.8
Avg	**2.52**	**5.48**	**9.9**	**10.5**

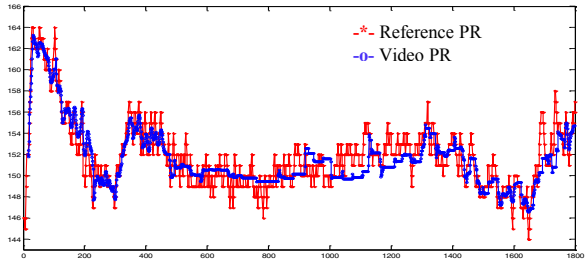

Figure 4: A plot of PR measured using the proposed system (video) against the hospital equipment (reference) in one subject as a function of time (s). [Note: In Table I, 5 ROIs were selected and size of each ROI is limited to at least 128x96 pixels in each video. This size is selected based on relative size of baby face to total image area.]

It can be seen that the mean bias for all 8 subjects is 2.52 bpm and 95% limits of agreement is ±5.48 bpm which is close to medical standards. The total measurement time for each subject is ~1800 seconds. Signals were isolated (i.e., not included) when excessive motion was detected. Last column in Table I represents the percentage loss of data in each video due to excessive motion. From the table, it is clear that much of the deviation occurred in neonates #4 and #6 and these subjects had very high derivatives in PR; 26 and 24 beat per square minute respectively. Also, the effect of motion recorded in the hospital equipment was not considered in these calculations. In Figure 4 capability of the proposed system is emphasized by showing the PR tracking results over time in one neonate as a function of time.

IV. CONCLUSIONS

The paper introduces a method for continuous PR monitoring without contact using a commercial HD webcam. Algorithms comprise of: (1) processing video frames to generate VPG signals representing cardiac functions in each of the batch, (2) stitching batches to generate continuous VPG signal, (3) automatic motion detection with video tracking of multiple selected ROIs of exposed skin regions, (4) compensating for motion with adaptive filter and (5) fusing results from multiple ROIs into one PR estimate using decision algorithms to generate the final PR results. Among the 8 subjects tracked over a period of 30 minutes each, excluding large motion, mean deviation was found to be 2.52 bpm and 95% limits of agreement ±5.48 bpm which is close to medical standards. Future work involves validation on more subjects (>100) and improving estimation accuracy under low light conditions (or without visible light) to be able to monitor under different NICU environments.

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