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Robust Design of Pulse Oximeter Using Dynamic Control and Motion Artifact Detection Algorithms

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Abstract – Arterial oxygen saturation (SpO_2) monitoring for newborns requires special attention in neonatal intensive care units (NICUs). Newborns have very low photo-plethysmogram (PPG) amplitudes and their body movements are difficult to contain. Hardware design and its associated signal processing algorithms should be robust enough so that faulty measurements can be avoided. In this study, improved designs were implemented to deal with low perfusion, motion artifact, and the influence of ambient light. Dynamic range was increased by using different LED intensities and a feedback system. To minimize the effects of motion artifact and to discard other unqualified data, four additional algorithms were used, which were based on dual-trace detection, continuity of DC level, morphology of PPG, and simultaneity check of SpO_2. Our SpO_2 system was tested with newborns with normal respiration in the NICU. Our system provided fast, real-time responses and 100% artifact detection was accomplished under 84% of SpO_2.

Keywords: Pulse oximetry, Motion artifact, Feedback control, Artifact detection algorithm.

1. Introduction

Pulse oximetry was developed in 1972 by T. Aoyagi and has been widely used since then, not only in university medical centers but also by private practitioners. The pulse oximeter is one of the best-selling medical devices in terms of quantities. Pulse oximetry is a non-invasive and non-constrained method of monitoring arterial oxygenation and pulse rate. Arterial oxygenation is estimated by the oxygen saturation of hemoglobin in arterial blood (SpO_2), which indicates the proportion of oxygenated hemoglobin (HbO_2) with respect to total hemoglobin [1, 2].

Pulse rate is one of the vital signs. The basic principle is to find absorptions on two different light-emitting diode (LED) wavelengths [3, 4]. It is one of the mandatory devices for monitoring the critical status of patients, regardless of gender or age [5, 6]. The SpO_2 of premature newborns in the neonatal intensive care unit (NICU) should be monitored continuously, as they are in critical condition [7, 8], and pulse oximeters are currently used for almost all of these neonates [9]. Despite all its merits, however, pulse oximetry use can be restricted under certain circumstances, such as body movement and low blood volume. In addition, varying degrees of ambient light and skin pigmentation also influence SpO_2 measurements [10, 11].

Newborns, in particular, have low perfusion and frequent body movements. Thus, in these patients, pulse oximetry has a high rate of false alarms that might be not within the acceptable range [12]. Various investigations have been carried out to minimize the rate of false pulse oximetry alarms in the NICU. In practice, however, the studies explored theoretical methods and simulations only. In addition, the computation to accomplish such tasks became too burdensome for producing commercial products [13-15].

In order to maintain reliable measurements, two approaches can be applied. First, signals with motion artifact are detected and discarded, as they occur intermittently. Second, distortions in photo-plethysmogram (PPG) waveform are minimized, and proper PPG signals are extracted. The second approach provides the advantage of monitoring PPG continuously, without sacrificing accuracy. Unfortunately, PPG may not be measured when waveforms are severely distorted [16]. Often, PPG data are stored, and the previous waveform stored in memory is displayed as the present one when severe distortion is detected. In our study, it was assumed that waveforms might be severely distorted in the NICU.

Signal-to-noise ratios (SNR) vary greatly, for several reasons. First, there are individual differences in PPG signal amplitude due to different blood volumes. Light transmission varies substantially depending on thickness and the pigmentation of the individual. Even in the same person, physiological status and room temperature can produce different PPG signal amplitudes. Ambient light is another important factor. Room illumination changes from day to night or at particular measurement times. In case of jaundice treatment for the vast majority of neonates, the intense white light of phototherapy impinges the photo-

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detector and SpO_2 can be underestimated. This is one of the most common problems in the NICU [17]. When using pulse oximetry in the NICU under an extreme environment, it is necessary to deal with a wide dynamic range. Finally, another constraint in developing a pulse oximeter is that signal processing should be simple enough to be able to perform in real time [18, 19].

The traditional algorithms of calculating pulse and SpO_2 detect peaks and troughs of the PPG signal in the time domain. To obtain reliable monitoring, three methods have been used. They are weighted moving average (WMA), Fast Fourier Transform (FFT) and Smoothed Pseudo Wigner-Ville distribution (SPWVD). The WMA method requires an 8-second period for satisfying clinical requirements [20]. FFT and SPWVD methods have too heavy computational burdens in order to be implemented in compact and inexpensive commercial products. In addition, these methods would take a long time to refresh pulse and SpO_2. This delay is regarded to be inappropriate for use in NICU.

In this study, hardware and firmware, as well as signal processing algorithms using reduced computations, were developed in order to apply our pulse oximetry design in the NICU environment. To increase the accuracy below 70% SpO_2, a calibrated table obtained from SpO_2 simulations was implemented in the system [21, 22]. Pulse oximeters based on our design were manufactured and tested with newborns in the NICU, and their performances were evaluated.

2. Methods

SpO_2 measurement becomes less accurate when there are low perfusion and motion artifact. Neonatal intensive care monitoring encounters most severe measurement environments. Neonates have extremely low perfusion and their motions are difficult to be controlled. The SNR and dynamic range were increased and the algorithms of detecting motion artifact were implemented. The influence of ambient light was minimized by baseline corrections using a feedback algorithm.

2.1 Hardware development

Our design of hardware configurations are shown in Fig. 1 as a block diagram. The system consists of three parts.

The sensing part housed a light source and silicon photo-diode. The light source had two LEDs, with wavelengths of 660 nm (red) and 870 nm (infrared). The analog part had an IV converter and AC amplifier. The probe that housed the light source and detector as well as electrical cables was shielded in order to prevent electromagnetic interferences. Both DC level and AC amplitude were extracted in order to compute SpO_2. OP amplifiers were used; their specifications were a maximum input bias

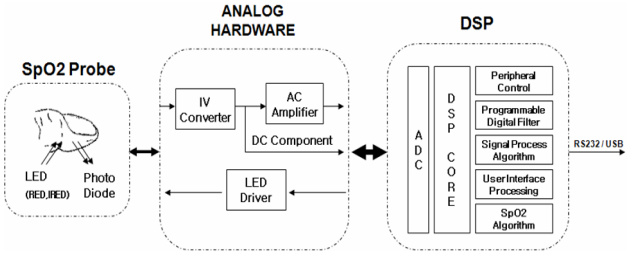

Fig. 1. Block diagram of basic hardware system.

current of 800 pA, a minimum CMRR of 60 dB, and a rail-to-tail type (Texas Instruments, Model TLV2264). The IV converter section contained a feedback circuit in order to minimize the influence of ambient light. Each LED signal was sampled at a rate of 300 Hz and converted into a digital signal. This signal was fed to a first-order RC low-pass filter whose attenuation was 6 dB at 16 Hz. The digital signal processing (DSP) chip was TMS320LF2406 (TI) based on 16-bit.

DSP performed bandpass filtering with cutoffs of 0.4 and 5 Hz, in order to display reliable waveform of red and infrared light in real time. During computing intervals (or pulse rate), infrared light was used. This infrared light was high-pass filtered with a 0.5 Hz cutoff once again, in order to minimize baseline drift. Digital filtering in DSP was designed using second-order infinite impulse response (IIR) filters. IIR filters are faster and require smaller memory size. The effect of phase delay observed with IIR filtering is not critical because PPG signal is in a very narrow frequency band.

2.2 Designs for increased performance

Our considerations for measuring SpO_2 and pulse rate in the NICU environment were capabilities of functioning reliably even under low perfusion, various transmission rates depending on individuals, and different intensities of ambient light. Therefore, an adaptive feedback system was implemented. Our SNR target was higher than 60 dB. First, the electrical cables for the photo diode and signal lines were electrically shielded. The setting of the IV converter gain was checked and tuned until better SNR values were obtained. The gain of the IV converter was set to 13 and that of AC amplifier was 39 (Fig. 1). To determine whether the SNR satisfied the design requirements, a SpO_2 simulator was used as a signal source. The perfusion index was set to the smallest value, and the signal and noise level values were measured.

Individuals have different skin pigmentations and thicknesses, which affects transmission rates. The location of the measurement is another variable, where variations in reflection angles and contact pressure produce different transmission rates. The LED light intensities were adjusted at two levels in our design. During measurement, the intensity level was automatically selected based on perfusion indices [23]. It is important that the light

intensity level should not be instantaneously changed, but follow a hysteresis response. For the change from high to low, the perfusion index (PI) should be higher than the previous PI value at which the change from low to high is made. Conversely, upon the change from low to high, the PI value should be lower than the previous PI value at which the change from high to low is made. This arrangement produces stable operations during intensity level changes. A simple test for wide dynamic range in practice can be performed with two measurement cases, one with two overlapped fingers and the other with an earlobe, representing the lowest and highest transmissions available.

Ambient light is another parameter that influences SpO_2 measurement. Ambient light comes not only from room illumination, but from the LED light itself. Red and infrared LED lights were driven by pulse width modulation (PWM) with a duty cycle of 40%. Measured ambient light was subtracted from the LED lights through negative feedback.

2.3 Signal processing algorithms in real-time

Peak detection is based on a reference trace method often used in pulse oximetry [24]. First, a reference trace is initialized at the beginning and compared to an infrared PPG signal. The reference signal is set to the PPG signal if it is less than or equal to the PPG signal. Then, the reference trace follows the PPG waveform. If the reference value becomes larger than the PPG signal, the reference trace follows a trajectory described as a second-order equation instead of following the PPG values. This point becomes one of peaks. A target of the trajectory is calculated by considering the period and amplitude of the previous pulse. The same routine is repeated. When the reference trace and PPG waveform meet once again, the reference trace follows the PPG signal. When the reference signal becomes larger than the PPG signal, this point becomes the next peak. The same type of tracing can also be made for PPG valleys.

This interval is the pulse period, and pulse rate is calculated from measured periods. From the values stored during the period, the peaks and valleys of the PPG waveform for both red and infrared light were computed. Using the peak and valley method, the ratio parameter for SpO_2 was computed [25]. A conversion table from ratio to SpO_2 was made using a SpO_2 simulator.

The DSP chip performed signal-processing tasks such as filtering, interval check, tracking DC and AC levels of PPG, and conversion from ratio parameter to SpO_2 values. The end results were SpO_2 and pulse rate values. Even with our robust hardware designs, wide dynamic range, and high SNRs, unrealistic values of SpO_2 and pulse rate can be shown. These are not proper values and are mostly generated by motion artifacts, and they should be discarded. Special algorithms to detect motion artifacts are proposed in this section. Real-time measurement placed limits on all signal processing, requiring that they be finished before the next sampling time, 3.3 ms in our case. Therefore, we are not able to use algorithms that cannot be carried out within this time constraint. Four algorithms to detect artifacts were implemented and they were based on dual-trace detection, continuity of DC level, morphology of PPG, and simultaneity check of SpO_2.

3. Results

Performances of Motion Artifact Detection Algorithms were examined and then experimental results were followed. First the dual-trace detection algorithm was tested. It could remove false PPG peaks effectively. Fig. 2 shows an example of a wrong peak that appeared due to motion artifact or physiological abnormality. Certain cases had a second inflection point with values that were higher or similar to those of the first inflection point. Both cases would detect a wrong PPG peak if one trace of tracking peaks, for example, was used for peak and interval detection. In the example shown in Fig. 2, another trace of tracking valleys was verified at the same time, called dual-trace detection. In other words, although the intervals were detected based on peaks, they were not counted as intervals unless the intervals were detected based on valleys as well.

Continuity of DC level was taken into consideration to detect motion artifacts. The DC level of a PPG waveform typically changes due to thoracic movement induced by respiration. DC level changes between the adjacent pulses due to respiration are seldom larger than 1% of the analog-to-digital converted DC values. Fig. 3 shows abrupt changes in DC levels due to motion artifact. For our device, a 1% reference was selected from experimental observations. Other oximeters may have different values, depending on electrical circuits and gain setting. For our system, it was satisfactory to determine that motion artifact occurred when the DC level change was greater than 1% of

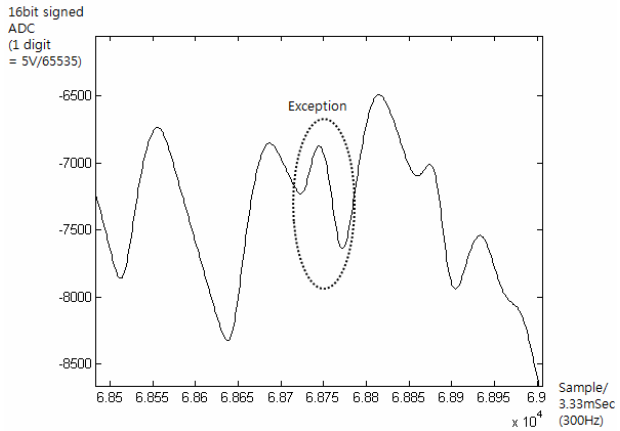

Fig. 2. An abnormal minor peak due to motion artifact or physiological abnormality

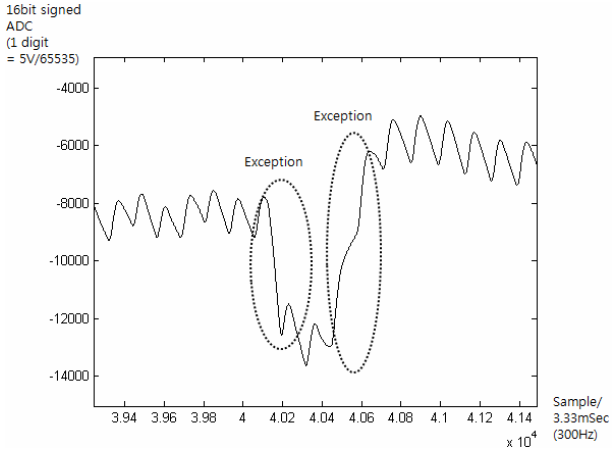

Fig. 3. DC levels encounter sudden changes due to motion artefact

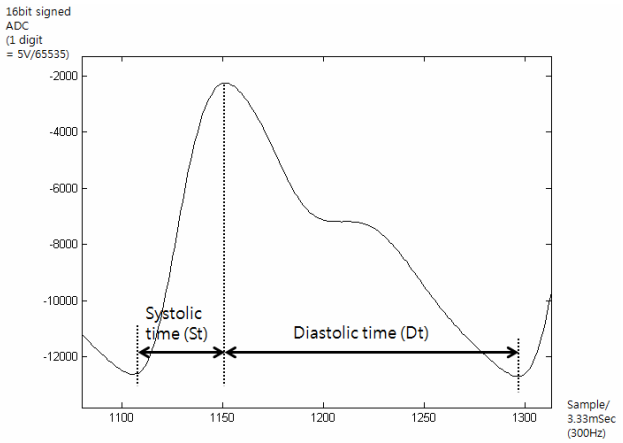

Fig. 4. Morphology of PPG where the systolic and diastolic time intervals are shown

the DC level of the previous pulse.

Another algorithm implemented in the system was associated with PPG morphology. PPG waveform reveals systolic and diastolic periods, and normal physiology can be one criterion for determining whether an artifact is included. Fig. 4 shows systolic period (St) and diastolic period (Dt). As the pulse rate increases, the durations of St and Dt decrease at the same time. However, in this example, the decrease in Dt is greater than the decrease in St. Pulse oximetry in our case covered 25-300 beats per minute, and pulse waveform was considered normal when the Dt/St ratio ranged between 2 and 25. Otherwise, the data were considered unqualified.

Another category for determining abnormal artifacts was based on simultaneity of PPG waveform. The maximum peaks of red and infrared light are shown in Fig. 5. When there are no noises or motion artifacts, the maximum and minimum of red light and those of infrared light should occur in the same timeframe. Intervals and AC amplitudes were calculated in three different ways.

First, the time interval was calculated by the peaks and valleys of infrared light, and then the peaks and valleys of

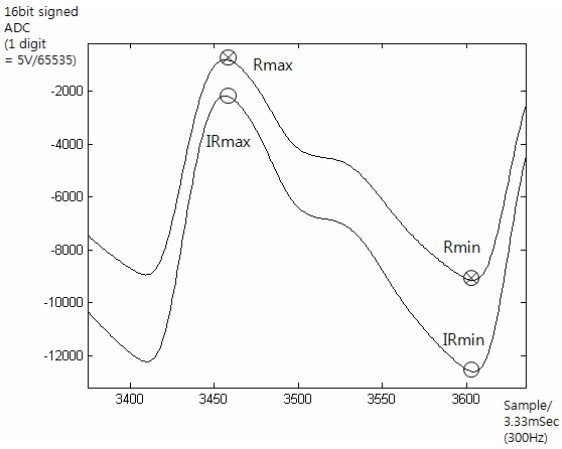

Fig. 5. How well peaks and valleys of IR and red light match to time-axis is used for simultaneity check for SpO_2

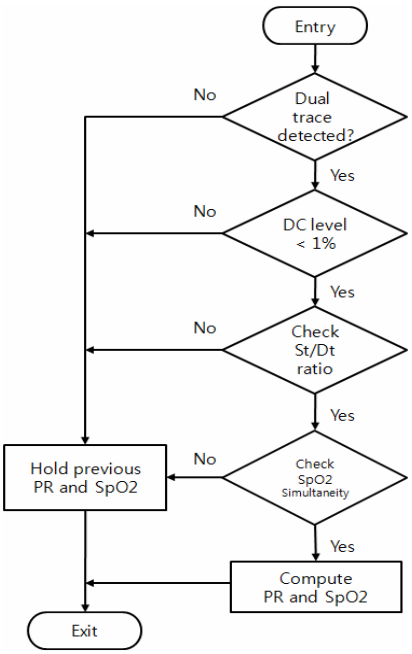

Fig. 6. Flowchart of the artifact detection algorithms

red light were computed within this time interval. Using these results, a SpO_2 value was calculated. In the second method, the reference time interval was chosen by the peaks and valleys of red light. Again, SpO_2 was calculated using this interval. In the third method, two different time intervals were used independently: infrared light analysis (i.e., computation of DC and AC amplitudes) based on the time interval selected by infrared light and red light analysis based on the time interval of red light. The three SpO_2 values computed using the three different methods should be almost the same if no artifacts occurred during measurement. In our study, differences greater than 2% of the SpO_2 values among the three methods were attributed to artifact.

Our signal processing steps for detecting artifacts are

summarized as a flowchart and shown in Fig. 6. First, it is checked whether two traces of following peaks and troughs are all present. Next, DC levels of the adjacent pulses are examined whether they are within 1 % difference. Then, the ratio between diastolic time and systolic time should be between 2 and 25. The final step is to compare all SpO_2 values computed from three different time intervals and to find whether they are within 2% of the SpO_2 values. Pulse rate and SpO_2 are calculated only when all four steps are satisfied simultaneously. Otherwise, the processor holds the previous value and waits for the next PPG signal to be processed.

Our hardware and algorithms were tested at the NICU at the University Hospital. Measurements were conducted on five newborns. At the time of the test, the ages and birth weights of the five subjects were 3 days old and 2918 g, 37 days old and 722 g, 4 months old and 544 g, 1 month old and 1793 g, and 34 days and 1512 g. The babies all had normal respiration. First, each baby was measured for 5 minutes. Disposable, reflection-type probes were attached on the instep. Normally, both reflection and transmission measurements lie within ±2% errors in the 70~100% range. The reflection probe is known to be more accurate for low oxygen saturation [26]. Each measurement was processed two times: once without artifact detection algorithms (called regular algorithm) and once using artifact detection algorithms.

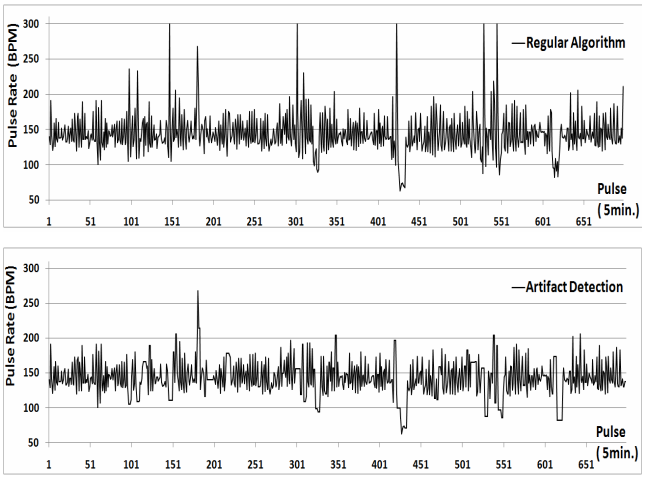

Fig. 7. Pulse rates before and after the application of the artifact detection algorithms.

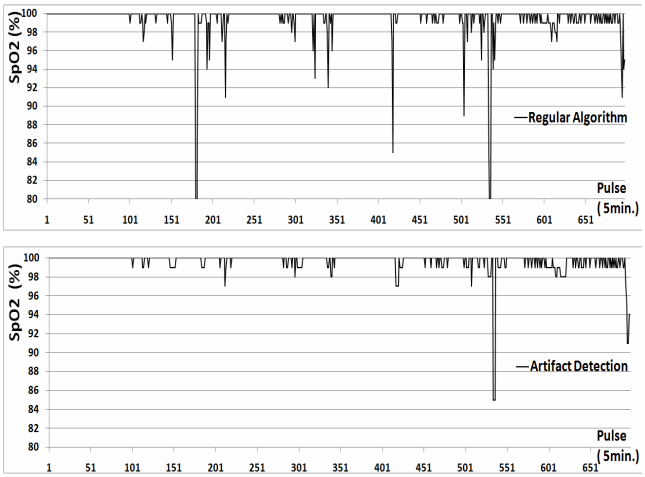

Fig. 8. SpO_2 before and after the application of the artifact detection algorithms

Measured data were signal-processed by a DSP chip in the oximeter and the output experiment data were 16-bit ADC data each for red and infrared light. Measured data were gathered through a serial network channel. In order to produce Figs. 2-5 and Figs. 7-9 in the manuscript, the same signal processing algorithms stored in the DSP chip were programmed in a PC using visual C^{++}. Regular algorithms and artifact detection algorithms were run and they produced values of pulse rate and SpO_2.

Figs. 7-8 show the examples of pulse rate and SpO_2 with respect to time during a period of 5 minutes. Fig. 7 shows pulse rates with and without artifact detection, and Fig. 8 depicts SpO_2 with and without artifact detection. As can be seen in the figures, motion artifact in newborns is a real issue, and it is not uncommon to hear false alarms in the NICU.

Fig. 9 shows the number of detected pulse rates or a distribution of measured pulse rates for all subjects. The regular algorithm did not use four additional algorithms to detect motion artifact or other abnormalities. The cases detected by our four algorithms as unqualified data were considered artifacts. Pulse rates between 100 and 180 beats per minutes (bpm) were in the normal range and accounted for 75.9%; 28.8% were discarded as unqualified data in this range. The highest distribution was around 160 bpm. Moving toward 25 bpm, the percentage of disqualification increased. For example, the unqualified rate between 25 and 60 bpm was 73 out of 92 (79.35%). A similar trend was observed toward 300 bpm. Between 250 and 300 bpm, 105 out of 130 (80.77%) measurements were diagnosed as artifact.

Table 1 shows artifact percentages of SpO_2 measure-

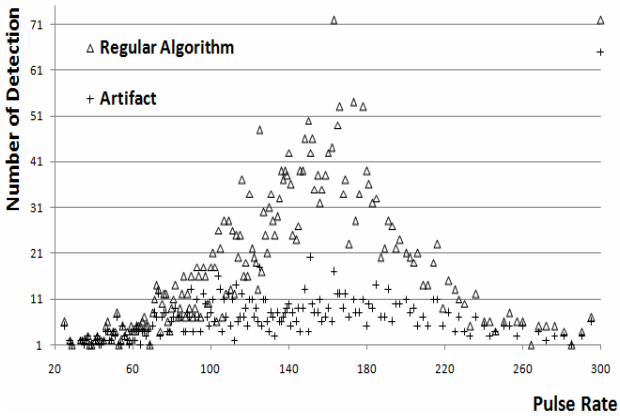

Fig. 9. Measured distributions of the pulse rate and predicted artifacts.

Table 1. Artifact percentages with respect to SpO_2.

SpO_2 (%)	Number of regular algorithm detection	Number of artifacts	Artifact regular detection (%)
83~34	43	43	100
84	3	2	66.67
85	6	4	66.67
86	3	2	66.67
87	5	3	60.00
88	3	1	33.33
89	17	10	58.82
90	14	9	64.29
91	25	16	64.00
92	22	14	63.64
93	40	27	67.50
94	42	30	71.43
95	53	31	58.49
96	56	39	69.64
97	71	50	70.42
98	100	64	64.00
99	328	154	46.95
100	2383	238	9.99

ments. Most measurements were distributed in the 93~100% range, which was considered the normal range; 3073 out of 3214 measurements (95.61%) were in the normal range, and 633 out of the 3073 measurements (20.60%) were found to be unqualified when the artifact detection algorithms were applied. When SpO_2 moved away from normal values to an unrealistic value of 34%, the percentages of unqualified data increased. Below 83% of SpO_2, all 43 measurements proved to be artifacts.

4. Discussion

One of the most important points in designing the electronic circuits of pulse oximeters is to provide PPG signals with a maximally available dynamic range, without sacrificing amplitude resolutions, regardless of patients or subjects. Generally there are significant individual variations in terms of path length, skin pigmentation, ambient light, and blood circulation. The NICU belongs to one of the extreme environments in pulse oximetry. Pulse oximetry should be robust enough to operate under this sever condition [27]. For this purpose, two approaches were undertaken; improvements of the signal-to-noise ratio (SNR) and abnormality detection algorithms.

For the cases of low light penetration or low perfusion, the amplitudes of PPG become small and white noise levels become substantial. Deteriorated amplitude resolutions reduce accuracy and, sometimes, it may be difficult to perform signal processing. In our investigation, shielded probes and amplifier designs higher than 60 dB were implemented. Even so, under certain circumstances, the intensity level of LED light needs to be changed due to large individual differences. Two intensity levels were assigned whose level was selected according to perfusion indices computed in real time. More than two intensity levels could have been assigned to increase dynamic ranges further. However, data acquired during intensity changes were not accurate as measurements were done with varying LED intensity. These data should not be used for analysis. Therefore more frequent changes in intensity levels would produce more invalid data. One had to wait until the LED amplitude stabilized, but no data would be available during this transition period. If LED intensity changes too rapidly, the system could become unstable in certain cases during feedback control. It was experimentally verified that two intensity levels produced satisfactory results under various conditions.

Another factor that influences SNR's is tolerance against ambient light. SpO_2 is based on optical measurements and is susceptible to external light. Red and infrared light illuminate alternatively and each data is sampled digitally and converted into digital data. In this investigation there was the period between red and infrared illuminations and signal during this period was measured as a reference signal. Unlike other devices this reference signal was fed back to input signal. Reference light was removed from input signal and the influence of ambient light was minimized. Even when a cigarette lighter flashed the SpO_2 probe, PPG signal was gathered successfully without any problem. Sampling rates were much faster than cigarette light and the external light flashed by the cigarette light was removed by the algorithm instantaneously.

Although all five subjects were in the NICU, they were not in critical condition, and they had normal respiration. Therefore, most irregularities or unqualified data observed during the experiment were expected to be the result of artifacts, and not actual physiological abnormalities. In five-minute measurements of five babies, 37.7% of the pulse rates and 22.9% of the SpO_2 values were found to be exceptions or unqualified data. The assumption of continuous artifact during monitoring makes it impossible for pulse oximetry, but in practice, that is not the case. It was expected that the removed data were incorrect values, as all five babies were healthy and were breathing smoothly during the experiment.

Most abnormalities of PPG signal are due to motion artifact. It is very important for algorithms to be fast without having too much computation burdens. Pulse oximetry should process data in real time. Another restriction might be the cost of high performance processors, which are valid for most pulse oximeters except a few high-end products. The main point of our proposed algorithms were targeted to detect artifacts and to remove them in real-time during calculations of pulse rates and SpO_2's. Our algorithms were not to predict PPG signal during motion artifact. There were reasons behind this approach. First, most motion artifacts occur suddenly and disappear quickly. Removal of SpO_2 reading during motion artifact does not pose critical problems when physicians monitor or evaluate clinical conditions of patients. Second, estimated or predicted PPG waveforms during motion artifact can hardly tell accurate

pulse rate and SpO_2. Even though PPG waveform may be extrapolate or interpolate just before or just after motion artifact, PPG signals during motion artifact are extremely difficult to be constructed especially when pulse rate and SpO_2 need to be monitored in real time. Applying excessive averaging or holding the previous value for some time is not recommended for neonates, whose irregularities are more severe than those of adults. Some commercial products average data excessively to overcome this problem, and they end up with slow response times and inaccurate data. Making decisions one at a time in real time, proposed in this study, is expected to be more useful.

5. Conclusion

In this study, hardware design and software algorithms were developed to enable real-time monitoring by removing data contaminated with motion artifacts or abnormalities not associated with actual health conditions. We increased the dynamic range of the detection system. For this purpose, LED intensity levels were changed and a feedback system was applied in order to maintain DC levels. Robust designs against external light or electromagnetic interferences were also implemented. More importantly, four algorithms were developed to detect abnormal data, based on dual-trace detection, continuity of DC level, morphology of PPG, and simultaneity check of SpO_2. Our device was successfully tested on newborns in the NICU of at the university hospital. Our system had a faster response and higher accuracy compared to other algorithms based on averaging or holding the measurement until stability regained.

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