Applied Ergonomics 56 (2016) 160–169

Contents lists available at ScienceDirect

Applied Ergonomics

journal homepage: www.elsevier.com/locate/apergo

Improving the detectability of oxygen saturation level targets for preterm neonates: A laboratory test of tremolo and beacon sonifications

Marie-Lys Deschamps [a], Penelope Sanderson [a, b, c, *], Kelly Hinckfuss [a], Caitlin Browning [a], Robert G. Loeb [d], Helen Liley [c, e], David Liu [b, c]

[a] School of Psychology, The University of Queensland, Australia
[b] School of ITEE, The University of Queensland, Australia
[c] School of Medicine, The University of Queensland, Australia
[d] Department of Anesthesiology, University of Arizona, USA
[e] Mater Mothers Hospital, Australia

A R T I C L E I N F O

Article history:
Received 17 November 2015
Received in revised form
22 March 2016
Accepted 23 March 2016

Keywords:
Patient monitoring
Pulse oximetry
Sonification
Auditory display

A B S T R A C T

Recent guidelines recommend oxygen saturation (SpO_2) levels of 90%–95% for preterm neonates on supplemental oxygen but it is difficult to discern such levels with current pulse oximetry sonifications. We tested (1) whether adding levels of tremolo to a conventional log-linear pulse oximetry sonification would improve identification of SpO_2 ranges, and (2) whether adding a beacon reference tone to conventional pulse oximetry confuses listeners about the direction of change. Participants using the Tremolo (94%) or Beacon (81%) sonifications identified SpO_2 range significantly more accurately than participants using the LogLinear sonification (52%). The Beacon sonification did not confuse participants about direction of change. The Tremolo sonification may have advantages over the Beacon sonification for monitoring SpO_2 of preterm neonates, but both must be further tested with clinicians in clinically representative scenarios, and with different levels of ambient noise and distractions.

1. Introduction

When the oxygen saturation of the arterial blood of a preterm neonate receiving oxygen support is too high or too low, it can lead to serious injury or even death. To avoid adverse outcomes, recent clinical guidelines recommend that neonatal arterial oxygen saturation levels determined using pulse oximetry (SpO_2) should stay within a narrow 90%–95% target range (Saugstad and Aune, 2014). However, as will be discussed, the current audible pulse oximetry tones are limited in how effectively they alert clinicians to SpO_2 changes away from that range.

In a recent study, Hinckfuss et al. (2016) added a reference tone, or "beacon", at regular intervals to the current pulse oximetry tones whenever SpO_2 levels were outside the neonatal target range. Non-clinician participants listening to simplified scenarios could identify general SpO_2 ranges and discriminate the target and non-target SpO_2 states more accurately with the beacon than without. However, potential disadvantages of the beacon enhancement were noted.

The study reported herein provides a further test of the beacon enhancement to the pulse oximetry tones. In addition, the present study tests another way of signalling whenever SpO_2 levels are outside the target range—by changing the quality of the pulse tones with 'tremolo', a vibrating characteristic added to the sound.

1.1. Pulse oximetry and the needs of preterm neonates

Pulse oximetry is a clinical monitoring technique that non-invasively estimates a patient's arterial oxygen saturation level by analysing light transmission though a vascular bed, such as in a finger or, for an infant, in the wrist, palm, or foot. Along with a visual display of HR and SpO_2, most pulse oximeters use 'sonification'—a continuous auditory display. A tone is played with every pulse, allowing estimation of pulse rate in beats per minute. The pitch of the tones represents SpO_2. A series of tones increasing

* Corresponding author. School of Psychology, The University of Queensland, Australia. Tel.: +61 407 288 695, +61 7 3346 9529.
E-mail address: uqpsande@uq.edu.au (P. Sanderson).

http://dx.doi.org/10.1016/j.apergo.2016.03.013
0003-6870/

or decreasing in pitch indicates rising or falling SpO_2 levels, respectively.

The current pulse oximetry sonification works well when the highest SpO_2 levels are also the target levels, but not if the target levels are in a lower range. In healthy adults, oxygen saturation levels typically remain between 100% and 97%. Therefore, for adults it is usually a good sign if the pitch of the pulse oximeter tones is increasing, and bad if the pitch is decreasing.

However, in preterm neonates, too much supplemental oxygen can lead to oxygen toxicity, development of bronchopulmonary dysplasia (Saugstad, 1997; Saugstad and Aune, 2014), and retinopathy of prematurity which can lead to blindness (Chow et al., 2003; Saugstad and Aune, 2014; Tin et al., 2001). Conversely, hypoxia (oxygen insufficiency) can damage organs, including the brain, contributing to cerebral palsy (Askie et al., 2011; Collins et al., 2001) and infant mortality (Dawson et al., 2010; Finer and Leone, 2009; Ford et al., 2006; Lim et al., 2014; Saugstad and Aune, 2014).

Therefore for preterm neonates monitored with the current pulse oximeter sonification, an increasing tone pitch could indicate either that the oxygen saturation level is becoming too high and the infant is at risk of oxygen toxicity, or that oxygen saturation is safely moving upwards towards the target zone. Likewise, a decreasing tone pitch could indicate either that oxygen saturation levels are moving safely downwards into the target range, or that hypoxia is imminent.

A further problem relates to knowing when the preterm neonate's SpO_2 has entered or exited the target range. Recent clinical guidelines recommend that neonatal SpO_2 should remain between 90% and 95% (Saugstad and Aune, 2014), but debate about the exact range continues (Manja et al., 2015). The current pulse oximetry technology does not provide SpO_2 range information in a manner that is suited to the clinical monitoring environment (Goos et al., 2013; Janata and Edwards, 2013; Lim et al., 2014; Tin and Lal, 2015). A recent study in two NICUs revealed that neonatal SpO_2 levels remained within a target range only 31% of the time, and were frequently outside it for prolonged periods (Lim et al., 2014). The longer and further a preterm infant's SpO_2 is outside target range, the higher the neonate's risk of adverse outcomes (Askie et al., 2011; Carlo et al., 2010; Lim et al., 2014).

1.2. Further challenges

Current pulse oximetry sonification relies on the clinician's ability to discern relative and absolute pitch (Brown et al., 2015). Multisensory training has been suggested as a way to improve clinicians' perception of the pitch of pulse oximetry tones (Schlesinger et al., 2014). However, this approach is unlikely to work across different pulse oximeter models, which use different mappings of tones to SpO_2 (Loeb et al., 2016; Santamore and Cleaver, 2004). Creating an auditory display design that makes deviations from target SpO_2 range obvious without the need for training could be a more robust approach to addressing the problem.

However, a redesign of the pulse oximetry sound for neonates must take into account the problem of adding extra sounds to an already demanding auditory environment. A major area of concern in all neonatal monitoring contexts is excess noise, which can lead to attentional narrowing, resulting in impaired monitoring performance (Hockey, 1997) as well as poorer health outcomes for patients (Long et al., 1980). Pulse oximetry devices use conventional auditory alarms alongside the variable-pitch sonification, so that their users also suffer from the well-documented disadvantages of auditory alarms (Edworthy, 2013; Edworthy et al., 2014; Lim et al., 2014). Neonates have higher heart rates than do adults, so variable pitch tones are emitted more frequently. In many NICUs, pulse oximeter variable-pitch tones are silenced to decrease the noise level, and intermittently-emitted earcons have been proposed as an alternative (Janata and Edwards, 2013). Within NICUs, clinicians rely on conventional threshold alarms to alert them to oxygenation deviations, given the impracticality of monitoring multiple pulse oximetry sonifications. During neonatal transport and resuscitation, clinicians are more likely to use the pulse tones as well as conventional threshold alarms.

Sonification offers several advantages. It may help to reduce reliance on alarms and may convey more information to the clinician. Sonification also supports eyes-free monitoring, where the patient's vital signs can be monitored in the clinician's peripheral awareness while other important tasks are performed (Watson and Sanderson, 2004; Woods, 1995). When a sonification is designed appropriately, changes in the sound should draw the clinician's attention to deteriorations in a patient's vital signs (Loeb and Fitch, 2002; Sanderson, 2006; Sanderson et al., 2009; Sanderson et al., 2005). A well-designed sonification should let clinicians maintain continuous awareness of the neonate's oxygen saturation levels during visually demanding tasks.

1.3. Recent enhancements of pulse oximetry sonification for neonates

Recently, Hinckfuss et al. (2016) examined whether a beacon, or reference tone, added to a simulated “log-linear” pulse oximetry sonification could improve detection of oxygen saturation deviations compared with the log-linear sonification alone. A log-linear sonification maps fixed increments of SpO_2 to a fixed percentage increase in frequency [Hz], thereby mapping a linear scale to a logarithmic one. Several conventional pulse oximetry sonifications use a log-linear mapping (Loeb et al., 2016). Previous research indicates that participants can identify SpO_2 values more accurately with a log-linear mapping than with a linear mapping (Brown et al., 2015), making the log-linear mapping a better control condition.

In the Hinckfuss et al. (2016) study, the beacon functioned as both an alert and a reference tone. It was played immediately before every fourth tone when oxygen saturation fell outside the 90%–95% target zone, alerting the listener to a non-target state. The pitch of the beacon was the same as the 93% oxygen saturation level, which is the middle of the target range, offering the listener a reference tone. When oxygen saturation levels were above the target range, the beacon was lower in pitch than the higher pitched heart rate tones, indicating the SpO_2 should decrease. When oxygen saturation levels were below the target range, the beacon was higher in pitch than the lower pitched heart rate tones, indicating that SpO_2 should increase.

When using the log-linear sonification with the beacon, participants could identify in which of five ranges SpO_2 fell with a 25-percentage point advantage compared with the log-linear sonification alone. However, the beacon sonification has potential drawbacks. First, it adds extra sounds to an already sound rich environment. Second, because the beacon is played only on every fourth heart rate tone, there may be a short delay between oxygen saturation going out of range, and the auditory signal of that change. Third, the listener must infer how far SpO_2 has deviated from the target range from the difference in pitch between the beacon and the tone.

In addition, there were shortcomings in the Hinckfuss et al. (2016) experiment and its findings. First, the effect of the beacon was tested within subjects: a clear between-subjects test would provide additional support for its effectiveness. Second, participants were not given a visual anchor of the SpO_2 range at the start of each trial, potentially making range identification unrealistically