Signaling Patient Oxygen Desaturation with Enhanced Pulse Oximetry Tones

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Abstract

Manufacturers could improve the pulse tones emitted by pulse oximeters to support more accurate identification of a patient's peripheral oxygen saturation (SpO_2) range. In this article, we outline the strengths and limitations of the variable-pitch tone that represents SpO_2 of each detected pulse, and we argue that enhancements to the tone to demarcate clinically relevant ranges are feasible and desirable. The variable-pitch tone is an appreciated and trusted feature of the pulse oximeter's user interface. However, studies show that it supports relative judgments of SpO_2 trends over time and is less effective at supporting absolute judgments about the SpO_2 number or conveying when SpO_2 moves into clinically important ranges. We outline recent studies that tested whether acoustic enhancements to the current tone could convey clinically important ranges more directly, without necessarily using auditory alarms. The studies cover the use of enhanced variable-pitch pulse oximeter tones for neonatal and adult use. Compared with current tones, the characteristics of the enhanced tones represent improvements that are both clinically relevant and statistically significant. We outline the benefits of enhanced tones, as well as discuss constraints of which developers of enhanced tones should be aware if enhancements are to be successful.

Pulse oximetry is widely used to monitor patient peripheral oxygen saturation (SpO_2) and pulse rate, mostly in the operating room (OR) and postanesthesia care unit. Evidence suggests that pulse oximetry helps clinicians reduce hypoxemic episodes,[1] though evidence for further clinical benefits to patients has been elusive.[1–3]

Since early in their development, pulse oximeters have emitted a tone with every detected pulse. The pitch of the tone is related to the measured saturation, and the repetition rate of the tone conveys the pulse rate, both of which assist clinicians in detecting changes. Although the variable-pitch tone has contributed to the success of the pulse oximeter by allowing eyes-free monitoring, room for further improvement exists.

The objectives of this article are to (1) review what is known about the variable-pitch SpO_2 tone and (2) outline the findings of research directed at making the tone more informative.

Including Pulse Oximetry Tone in the User Interface

The Nellcor pulse oximeter patent, initially filed in 1982,[4] includes a claim for a variable-pitch tone, and Nellcor pulse oximeters were the first to emit "a tonal signal ... having a pitch proportional to the ratio of SpO_2 and a sequential repetition proportional to pulse." Nellcor made the technique available to the public in the 1992 ASTM F1415 standard, which became ISO 9919, which in turn was superseded by ISO 80601-2-61. Thereafter, some implementation of a variable-pitch tone was included on most clinical pulse oximeters.

In a tribute article to Dr. Takuo Aoyagi, the inventor of pulse oximetry, contributors mentioned the power of the variable-pitch tone.[5] For example, Jeff Cooper noted, "Perhaps, the most appealing feature was the changing sound of the pulse tone with decreasing saturation" and the impact of "the confidence during intubation on hearing that so recognizable tone indicating the state of saturation." In the same article, a group from Lifebox Foundation noted that "anesthesia providers often refer to their pulse oximeter as their 'eyes and ears.'"

In 1982, electrocardiogram (ECG) monitors already emitted a tone with every heartbeat, but with fixed pitch. The idea to map tone pitch to SpO_2 was a well-justified choice. As a systematic review has shown,[6]

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pitch is the most commonly used auditory dimension to convey quantity, whether on a continuum or in discrete steps. Moreover, increases in pitch are almost universally associated with increases in quantity, whereas decreases in pitch are associated with reductions in quantity. The pulse oximetry standard ISO 80601-2-61:2019[7] does not require a tone; however, if a tone is provided, the standard does require that "the pitch change shall follow the SpO_2 reading (e.g., the pitch decreases as the SpO_2 reading decreases)" (section 201.102, p. 23).

The advantage of the variable pitch for conveying desaturation is so self-evident that only one study seems to have been needed to demonstrate it. Craven and McIndoe[8] showed that with a fixed-pitch pulse oximeter tone, desaturation was detected in an average of 129 seconds, but the variable-pitch tone allowed desaturation to be detected in an average of 32 seconds—a fourfold advantage.

Pulse oximetry was included in the original 1986 American Society of Anesthesiologists (ASA) monitoring standards,[9] but the standards did not mention the tone. Nonetheless, use of the tone was strongly encouraged by the anesthesia community. For example, in 2004, Goldman and Robertson[10] asked, "Isn't it time that we mandate the use of the pulse oximeter pulse tone for the monitoring of all patients undergoing general anesthesia and incorporate this requirement in the ASA Standards for Basic Anesthetic Monitoring? If so, we must explore related issues, such as the necessity of standardizing the pulse oximeter's pitch-saturation values."

Around the same time, Stoelting[11] noted "the audible presence of the 'beep' tone from the pulse oximeter, plus knowing that the audible alarm on at least one physiologic monitor of the anesthesiologists' choice ... is active, would provide the desired safety net to the anesthesiologists' eternal vigilance." After 2005, in response to such observations, the ASA standards for basic anesthetic monitoring were revised to require that "when the pulse oximeter is utilized, the variable-pitch pulse tone and the low threshold alarm shall be audible to the anesthesiologist or the anesthesia care team personnel" (section 2.1.2, p. 2).

Studies Describing Problems with Pulse Oximeter Tone

Despite the above, the effectiveness of the current pulse oximeter sound is limited. First, when listening to changes in the variable-pitch tone, listeners tend to underestimate how much SpO_2 has changed. Second, in certain clinical situations, knowing the clinical range in which SpO_2 lies is critical, but SpO_2 range is not readily conveyed with the current types of tones. These issues are addressed below. A glossary of terms appears in Table 1.

A few years after the pulse oximeter's introduction in the U.S., Schulte and Block[12] found that only 67% of their nonclinician participants could detect a single-step drop in the SpO_2 tone of the Nellcor pulse oximeter and 11% of participants required seven successive drops of the SpO_2 tone before they reported a change in saturation. However, as Santamore and Cleaver[13] and Loeb et al.[14] have shown, the Nellcor tones have a relatively small pitch range and small pitch increments (5 Hz) compared with other monitors, possibly contributing to Schulte and Block's findings. Still, using the more generous step sizes of the Datex AS3 tones, Morris and Mohacsi[15] showed that anesthesiologists systematically underestimate degrees of desaturation below 90% SpO_2, and only 70% of their sample could identify the direction of change for two tones one step apart. Similar findings were reported by Perez et al.,[16] with particularly inaccurate estimates of SpO_2 values when the tone was decreasing.

The participants in the above studies made their judgments in ideal situations away from the distractions and noise of the OR. However, distractions and noise probably would lead to worse performance. Stevenson et al.[17] evaluated anesthesiologists' ability to detect a drop from 99% to 98% saturation on a simulated Philips MP70 monitor, under different controlled conditions of background noise and visual attentional load. Noise reduced the anesthesiologists' accuracy at detecting the drop by around 10 to 15 percentage points and increased their response times by approximately 50 ms. Moreover, high visual attentional load decreased accuracy by around 5 percentage points and lengthened response times by approximately 125 ms.

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Term	Definition (Informal)	Description of Use in Current Research Program
Amplitude	Measure of the maximum pressure displacement of a sound wave. Measured in dB.	Amplitude is the physical property experienced as loudness or softness when applied to tones.
Beacon	A tone that provides an anchoring reference sound against which other sounds can be compared.	Beacon plays intermittently when SpO_2 is not in target range to remind listener what the middle of the target range for SpO_2 sounds like.
Brightness	Higher harmonic content of a sound, as opposed to dullness which is lower harmonic content. Also see timbre.	Brightness is the shrillness or sharpness of a tone, and dullness refers to the smoothness of a tone. Used to emphasize different SpO_2 or BP ranges.
Chirp	A tone with a rapidly rising or falling frequency across its duration.	A chirp is experienced as a tone with either rapidly rising pitch (as with a bird's "tweet") or rapidly falling pitch.
Formant	A specific pattern of harmonics that characterizes specific vocal tracts.	Formants suggesting different vowel sounds are used to emphasize different SpO_2 ranges.
Frequency	For sound, the number of pressure displacement cycles per unit of time for a tone. Physical property experienced as pitch measured in cycles per second (Hz).	Frequency is applied to tones to represent SpO_2 percentage saturation numbers.
Fundamental frequency	Lowest frequency in a tone that has more than one frequency.	See entry for harmonics.
Harmonics	Co-occurring sound frequencies that are integer multiples of the fundamental frequency.	Harmonics are experienced as the timbre or brightness (sharpness, dullness) of a tone.
Linear mapping	Frequency step sizes that are a fixed value across adjacent steps in an ordered set of frequencies (e.g., step sizes of 5 Hz).	Not used in current research program. Linear mapping would make pitch changes across SpO_2 steps seem smaller as tone pitch increases.
Logarithmic mapping	Frequency step sizes that are a fixed ratio across adjacent steps in an ordered set of frequencies (e.g., frequency step increases of 1.86%).	Logarithmic mapping is used to make pitch differences across SpO_2 step changes appear to be the same size (see Figures 1 and 3).
Loglinear mapping	Mapping of a linear quantity to a logarithmic quantity.	Loglinear mapping is used to describe conditions in which linear increases in SpO_2 number are mapped to logarithmic increases in sound frequency.
Loudness	The subjective experience of sound amplitude.	Loudness is the relative sound intensity of tones (loudness or softness).
Pitch	The subjective experience of sound frequency. Measured on the mel scale (scale of pitches whose steps seem equal in size).	Applied to tones to represent different SpO_2 percentages, with high pitches representing high SpO_2 and low pitches low SpO_2.
Pointer	Formal term for a beacon.	See entry for beacon.
Semitone	A frequency step increase of approximately 5.95%.	Not used in current research program.
Timbre	Quality of a sound due to its harmonics, as might be found in different musical instruments.	Timbre is used describe the manipulation of harmonics to create brightness or dullness of tone quality. Used to emphasize different SpO_2 or BP ranges.
Tone	A sound of fixed duration, sometimes with a single fixed frequency.	Tone refers to an individual beep of the pulse oximeter.
Tremolo	A rapid oscillating (cyclical) amplitude modulation of a tone (e.g., between 10% and 100%), giving it a "corrugated" effect.	Different tremolo rates are used to emphasize different SpO_2 HR, or BP ranges. Expressed as cycles per tone duration.
Vibrato	A rapid oscillating (cyclical) frequency modulation of a tone (e.g., between 440 and 450 Hz), giving a wavering effect to the pitch heard.	Not used in current research program.

Table 1. Glossary of acoustic terms used in the current work. Abbreviations used: BP, blood pressure; HR, heart rate; SpO_2, peripheral oxygen saturation.

The above studies of listeners' perceptions of pulse oximeter tones were performed with different pulse oximeter models. Several studies have noted the different mappings of the pitch of tones to SpO_2 levels across brands, which may compound the difficulties that anesthesiologists have with interpreting the

variable-pitch tone, especially when moving between pulse oximeters made by different companies.[13,14,18] The study by Loeb et al.[14] is the most comprehensive, showing that of 10 representative models, none had the same mappings. Differences existed in whether there was a linear or logarithmic mapping of pitch increments to saturation increments, whether pitch changed on each saturation change or every second change, whether pitch changes occurred for all saturation levels or stopped changing below a certain level, and in the actual pitch ranges and component frequencies used for the tones. The article revisited the need to consider standardization of pitch mappings to SpO_2, as Goldman and Robertson[10] had advised more than 10 years earlier.

However, there are deeper problems. The enthusiasm for the variable-pitch pulse oximeter tone is based on its ability to signal change and its ability to signal whether SpO_2 is increasing or decreasing. Notwithstanding the above studies, humans have good *relative* pitch, meaning that except in the closest cases they can tell if a tone has changed and whether its pitch is going up or down, even if they cannot judge by how much. However, most humans do not have good *absolute* pitch.[19] Translated to the clinical context, good absolute pitch would mean being able to identify the exact SpO_2 number on hearing a single pulse oximeter tone (or repetitions of that tone), without looking at a visual display and without hearing tones at a prior known value.

Knowing the clinical range or even the absolute saturation may be desirable in some situations. For example, hyperoxygenation can be harmful in certain clinical cases (e.g., preterm neonates, long-term critical care); therefore, the target saturation is less than 100% and a higher pitch is not necessarily better. In another example, clinicians may intervene to correct a patient's hypoxemia (desaturation) and cease intervening after they hear the tone indicating that saturation is increasing. However, SpO_2 may still be below target level, which would not be revealed until the clinician checked the visual indicator. Accordingly, researchers have taken steps to improve how effectively clinicians can identify the clinical range or even the absolute SpO_2 number from the sound of the variable-pitch tone alone.

Studies Training the Listener

Attempts have been made to improve perception of pulse oximeter pitch changes using multisensory training.[20] Anesthesiologists were trained to detect temporal differences in the onset times of a visual and auditory stimulus. After training, the anesthesiologists detected pitch changes 9% more accurately and 72 ms faster than in their pretraining performance, taken across different levels of ambient noise and visual attentional load. The findings were particularly strong with high levels of ambient noise. Training and the test of pitch perception were on separate days, but it is unclear how long the advantage of multisensory training would persist. In addition, as recognized in hierarchy of effectiveness schemes, changing human performance through training or education generally is a less desirable and less effective approach than changing performance through design.[21]

Signaling SpO_2 Ranges with Pitch Step Sizes

As noted above, Loeb et al.[14] demonstrated the wide variability in how frequency is mapped to SpO_2 across current pulse oximeters. Some devices map frequencies linearly to SpO_2, and others map frequencies logarithmically. Logarithmic mappings create approximately equal-appearing pitch intervals between SpO_2 levels, closer to the mel scale[22] of perceived-as-equal pitch intervals. Brown et al.[23] demonstrated that clinicians make more accurate estimates of SpO_2 values when the values are mapped logarithmically, with each step the equivalent of a semitone. They found that when SpO_2 values were mapped linearly, clinicians underestimated the change from a reference tone, as also reported by Morris and Mohacsi.[15] With logarithmic steps, clinicians also identified direction and percentage change from a reference tone more accurately. However, tests were always done relative to an anchoring reference sound.

Some studies have attempted to improve the way sound frequencies are mapped to

SpO_2 levels. An initial attempt at signaling acoustically when SpO_2 goes into a nontarget range was done by Hinckfuss et al.[24] in a neonatal context. The pitch step sizes in the target SpO_2 range were kept quite small, but as soon as SpO_2 went into a low or high range, pitch step sizes between saturation levels increased. However, this approach did not improve listeners' ability to identify which range SpO_2 was in, compared with a logarithmically mapped scale using consistent step sizes.

Signaling Loss of Pulse Oximetry Signal with Acoustic Enhancements

Some multiparameter monitors alter the pulse oximeter sound quality when pulse oximetry is not used or the pulse oximeter signal is lost. In this situation, a fixed-pitch tone is emitted with every ECG-detected heartbeat. The ECG tone is given a different sound quality (timbre) from the pulse oximetry tone to prevent it from being mistaken for a pulse oximetry tone. As discussed below, a similar approach can be used to convey other information.

Signaling SpO_2 Ranges with Acoustic Enhancements

Neonatal Pulse Oximetry

Direct comparisons of enhanced pulse oximetry tones with a version of the current pulse oximetry tones have been motivated by the challenge of avoiding hyperoxemia when providing supplemental oxygen to preterm neonates. According to the NeoPROM trial, SpO_2 of preterm neonates should be kept in a target range of 90% to 95% SpO_2 to optimize survival without hyperoxia- or hypoxia-associated morbidity.[25] As noted by Hinckfuss et al.[24] an increase in the pitch of the pulse oximetry tone is ambiguous for this population, as it could indicate a return from low levels to the target range or from the target range to high levels. The reverse problem holds for decreases in the pitch of the tone.

Accordingly, a program of research has investigated ways of enhancing the existing pulse oximetry tone to make it clear when SpO_2 is very low, low, target, high, or very high (Figures 1 and 2, and Appendix 1 [available in the supplemental material for this article at www.aami.org/bit]). In each experiment, the control and enhanced

Loglinear				Enhanced condition				
Range	SpO2 (%)	Hz (Set A)	Hz (Set B)	Range	SpO2 (%)	Hz (Set A)	Hz (Set B)	Additions
Very high	100	881	950	Very high	100	881	950	Second level
	99	858	933		99	858	933	
High	98	836	916	High	98	836	916	First level of acoustic enhancement
	97	815	899		97	815	899	
	96	794	882		96	794	882	
Target	95	774	866	Target	95	774	866	No enhancement
	94	754	850		94	754	850	
	93	735	835		**93**	**735**	**835**	
	92	716	820		92	716	820	
	91	698	805		91	698	805	
	90	680	790		90	680	790	
Low	89	663	775	Low	89	663	775	First level of acoustic enhancement
	88	646	761		88	646	761	
	87	629	747		87	629	747	
	86	613	734		86	613	734	
	85	597	720		85	597	720	
	84	582	707		84	582	707	
Very low	83	567	694	Very low	83	567	694	Second level of acoustic enhancement
	82	553	681		82	553	681	
	81	539	669		81	539	669	
	80	525	657		80	525	657	

Figure 1. Illustration of the mapping of frequency (in Hz) and clinical ranges to peripheral oxygen saturation (SpO_2) levels used in three studies relating to neonatal pulse oximetry. *Left:* The "loglinear" condition with no enhancements. *Right:* The "enhanced" condition that added further acoustic properties (see text) to the tones as SpO_2 moved further away from the target zone. For studies in which beacon enhancement was used, the beacon was always set to an SpO_2 of 93% (see boldface data in enhanced condition). In some studies,[24,26] the mappings of SpO_2 to Hz shown in set A were used for all conditions, whereas in other studies,[27] set B (recommended by Loeb et al.[14]) was used for all conditions. For studies in which the mapping of ranges to Hz varied, depending on the number of minutes after birth,[29,30] set B was used for all conditions and mappings extended below an SpO_2 of 80%. Other mappings of ranges, tone frequency in Hz, and SpO_2 are possible.

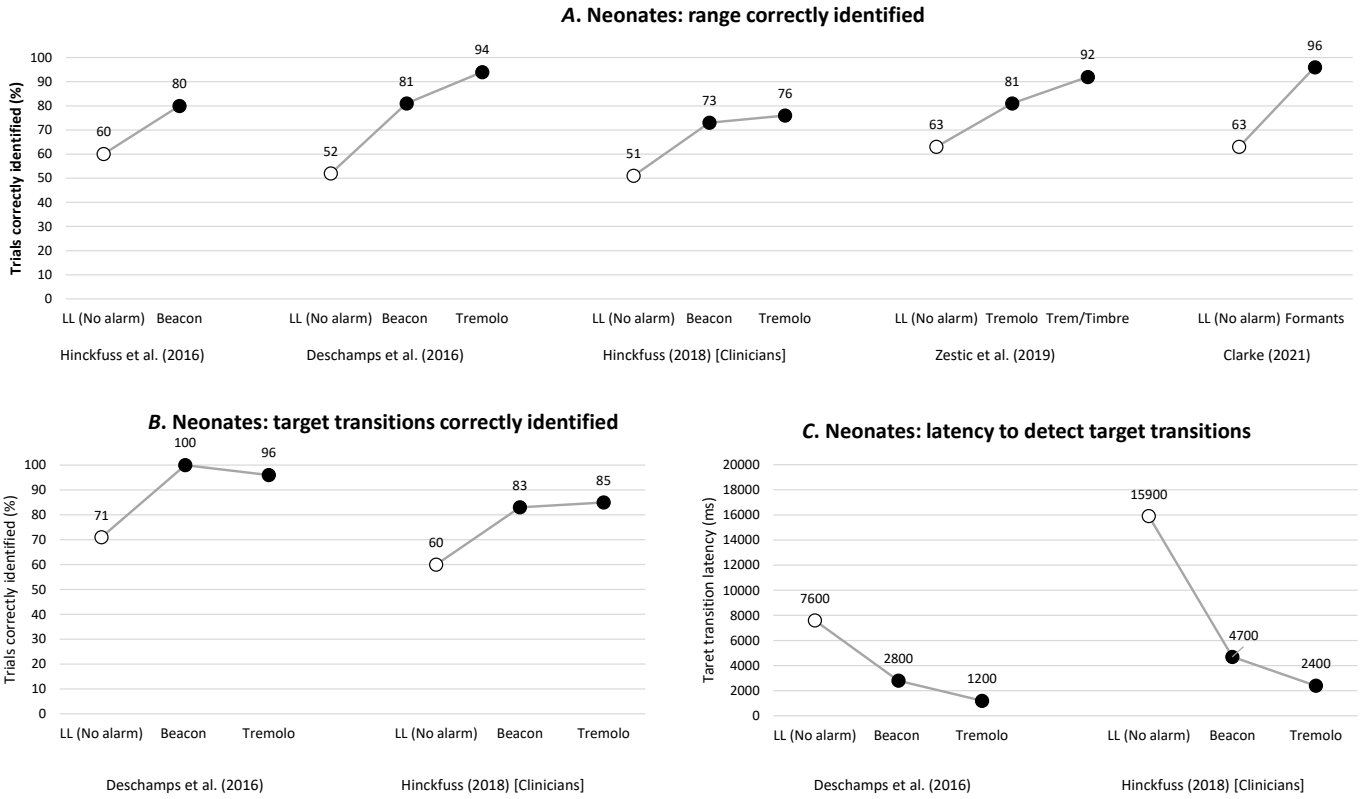

Figure 2. Illustration combining the findings of five studies investigating the impact of discrete acoustic enhancements on participants' judgment of neonatal pulse oximetry tones.[24,26,27,29,30] LL refers to loglinear mapping of peripheral oxygen saturation (SpO_2) to tone frequency (in Hz); all conditions used a loglinear mapping. White circles represent control conditions and black circles enhanced conditions. In all studies, performance in the enhanced conditions was significantly better than in the control conditions. Abbreviation used: trem, tremolo.

conditions used tones with a logarithmic mapping of sound frequency to SpO_2 levels, creating equal-appearing pitch intervals across the range of SpO_2 levels. For the more recent studies in this series, saturation of 100% was 950 Hz and 0% was 150 Hz. These values follow the recommendations given in Loeb et al.[14] Several types of enhancements have been tested. For example, the tone itself might acquire tremolo (rapid repeated changes in volume), a different timbre (manipulation of harmonics to create a sharper or duller sound), or both. Alternatively, an extra tone (a "beacon" or, more formally, a "pointer") might sound before every nth tone to alert the listener that SpO_2 is not in the target zone and to remind them what pitch the main tone would be if it were in the target range. Examples of these enhancements are provided in sample audio files, which are included in the supplemental material for this article (at www.aami.org/bit).

Figure 2 shows the results of five studies evaluating enhanced pulse oximetry tones designed to enhance neonatal monitoring. The first three studies assumed a consistent target range of 90% to 95% SpO_2.[24,26,27] Participants listened to short scenarios during which the pulse oximetry tone varied. At the end of each scenario, they identified the ending saturation range. In two studies, the participants also responded during the scenario if they heard the pulse oximetry tone go into or out of the target range.[26,27] Substantial improvements occurred in range identification (Figure 2*A*), target transition identification (Figure 2*B*), and latency to detect target transitions (Figure 2*C*) with the beacon and with the tremolo enhancements, though results for the tremolo enhancements were slightly more impressive. With tremolo, range identification improvements varied between 20–42 percentage points, target transition improvements were 25 percentage points in both studies, and the latency for detecting transitions sped up by 5.4 seconds in one study and by 13.5 seconds in a further study with clinical participants.

The two rightmost studies in Figure 2*A* are from studies examining oxygen targeting in the first 10 minutes after birth, where the target saturation increases each minute from around 60% to above 90%,[28] creating a dynamically changing target range. In one experiment, Zestic et al.[29] enhanced the variable-pitch pulse oximetry tone with different degrees of tremolo in the high and low SpO_2 range. In a second experiment, they added a sharp-sounding timbre in the high SpO_2 range. The SpO_2 values deemed to be low or high, and therefore subject to the enhancements, changed minute by minute. The tremolo enhancement produced an 18 percentage point improvement in SpO_2 range identification, and the addition of timbre in the high SpO_2 range led to a 29 percentage point improvement in SpO_2 range identification. In another study, Clarke[30] used formants to distinguish ranges (formants are vowel sounds such as "ee" for high SpO_2 range, "ah" for target range, and "oh" for low range) and achieved even more dramatic results, with a 33 percentage point improvement in SpO_2 range identification.

Despite minor procedural differences among the studies described above and the different acoustic enhancements tested, the studies consistently showed substantial improvements in performance with acoustic enhancements to the variable-pitch pulse oximetry tone. Further work will include simulation studies and clinical trials.

Other studies that have addressed neonatal pulse oximetry sounds are less relevant for the present context. A study by Janata and Edwards[31] proposed intermittent earcons (short abstract auditory motifs) rather than continuous sonification and therefore has a somewhat different purpose. A study by Schwartz and Ziemer[32] used continuously ascending or descending Shepard's tones[33] to indicate when SpO_2 was in ranges above or below target. However, these researchers performed no determination of whether participants would confuse SpO_2 range with SpO_2 direction and rate of change.

Adult Pulse Oximetry

Acoustic enhancements have also been applied to adult SpO_2 ranges (Figures 3 and 4, and Appendix 1). In a series of studies, Paterson and colleagues[34–37] enhanced the variable-pitch tone to distinguish three ranges: target, warning, and critical. In each study, SpO_2 tones in the warning range were enhanced with four cycles of tremolo, and tones in the critical range were enhanced with tremolo plus a constant level of "bright" timbre. In contrast to the neonatal studies, for the adult studies the unenhanced variable-tone pulse oximetry sound was supplemented with an alarm at the boundary between the warning and critical level, creating a control condition closer to common clinical practice.[34,36,37] Two of the studies included clinician participants, both in a desktop study[34] and in a full-scale simulation study.[37]

As Figure 4 indicates, all studies showed marked improvements with the enhanced pulse oximetry sounds for range identification, target transition identification, and latency to detect target transitions. Range identifications improved between 10 and 43 percentage points, target transition identifications improved between 26 and 40 percentage points, and latency to detect target transitions sped up by 7.6 seconds in one study[34] and by 22.3 seconds in another.[37]

In two of the studies, participants were asked to estimate the absolute SpO_2 value.[34,36] Responses were considered correct if they were within 1 percentage point of the correct answer. Absolute accuracy performance increased by 17 percentage points in one study[36] and 21 percentage points in another.[34]

In all the neonatal and adult studies shown in Figures 2 and 4, the enhancement took the form of a substantial discrete change in the quality of the pulse oximetry sounds in different ranges, rather than small incremental changes with each percentage change in SpO_2. To test whether there was any advantage in using small incremental changes, Collett et al.[38] compared enhancements using discrete changes across ranges with enhancements that gradually increased tremolo and the brightness of timbre within ranges as they got further away from the target range. With the discrete changes, range identification was 9 percentage points more accurate compared with the incremental changes, target transition identification was more accurate by 18.5 percentage points,

Loglinear				Enhanced condition				
Range	SpO_2 (%)	Hz (Set A)	Hz (Set B)	Range	SpO_2 (%)	Hz (Set A)	Hz (Set B)	Additions
Target	100	881	950	Target	100	881	950	No acoustic enhancement
	99	858	933		99	858	933	
	98	836	916		98	836	916	
	97	815	899		97	815	899	
Warning	96	794	882	Warning	96	794	882	First level of acoustic enhancement
	95	774	866		95	774	866	
	94	754	850		94	754	850	
	93	735	835		93	735	835	
	92	716	820		92	716	820	
	91	698	805		91	698	805	
	90	680	790		90	680	790	
Critical	89	663	775	Critical	89	663	775	Second level of acoustic enhancement
	88	646	761		88	646	761	
	87	629	747		87	629	747	
	86	613	734		86	613	734	
	85	597	720		85	597	720	
	84	582	707		84	582	707	
	83	567	694		83	567	694	
	82	553	681		82	553	681	
	81	539	669		81	539	669	
	80	525	657		80	525	657	

Figure 3. Illustration of the mapping of frequency (in Hz) and clinical ranges to peripheral oxygen saturation (SpO_2) levels in studies of adult pulse oximetry. *Left*: The "loglinear" condition with no enhancements. *Right*: The "enhanced" condition that included further acoustic properties (see text) to the tones as SpO_2 moved further away from the target zone. The earliest study[35] used the set A mapping of SpO_2 to Hz in both conditions. The later three studies [34,36,37] used the set B mapping in both conditions. Other mappings of ranges, tone frequency in Hz, and SpO_2 are possible.

and latency was faster by more than 5 seconds, underscoring the importance of discrete changes in the enhancements.

General Observations

The benefits of acoustic enhancements appear to overwhelm the impact of distractions, such as noise or time-shared tasks.[17,20] Two of the neonatal studies shown in Figure 2 included a time-shared arithmetic task[29,30] and one included both the arithmetic task and OR noise.[27] Three of the adult studies shown in Figure 4 combined time-shared tasks, ambient pop music, and OR noise.[34,36,37] Markedly better performance was seen with the enhanced tones, despite these distractions. A further benefit is that the acoustic enhancements require only familiarization, rather than end user training, to be used effectively. A final benefit is that all participants, including clinicians, rated it easier to use the enhanced pulse oximetry tones than current pulse oximetry tones, and they rated their confidence in their judgments higher. Clinicians' qualitative comments after the simulation study[37] underscored the greater effectiveness and potential clinical usefulness of the enhanced tones.

Using acoustic enhancements to signal clinically significant saturation ranges is effective, whereas using them to convey blood pressure (BP) values seems not to be effective. There are no clear demonstrations that listeners monitor BP more effectively either when the pulse oximeter tone is modified,[39,40] when a separate BP-specific sound feature is added,[41] or when multiple vital signs are mapped to different musical instruments.[42,43] Due to the complexity of monitoring three vital signs (heart rate [HR], SpO_2, and BP), responses to changes in HR and SpO_2 may become less accurate in an auditory display that includes all three rather than two vital signs. Even with just the two standard pulse oximetry parameters (HR and SpO_2), attempts to indicate high, target, and low HR ranges with further acoustic enhancements (i.e., in addition to the SpO_2 enhancements) have not led to a benefit.[30]

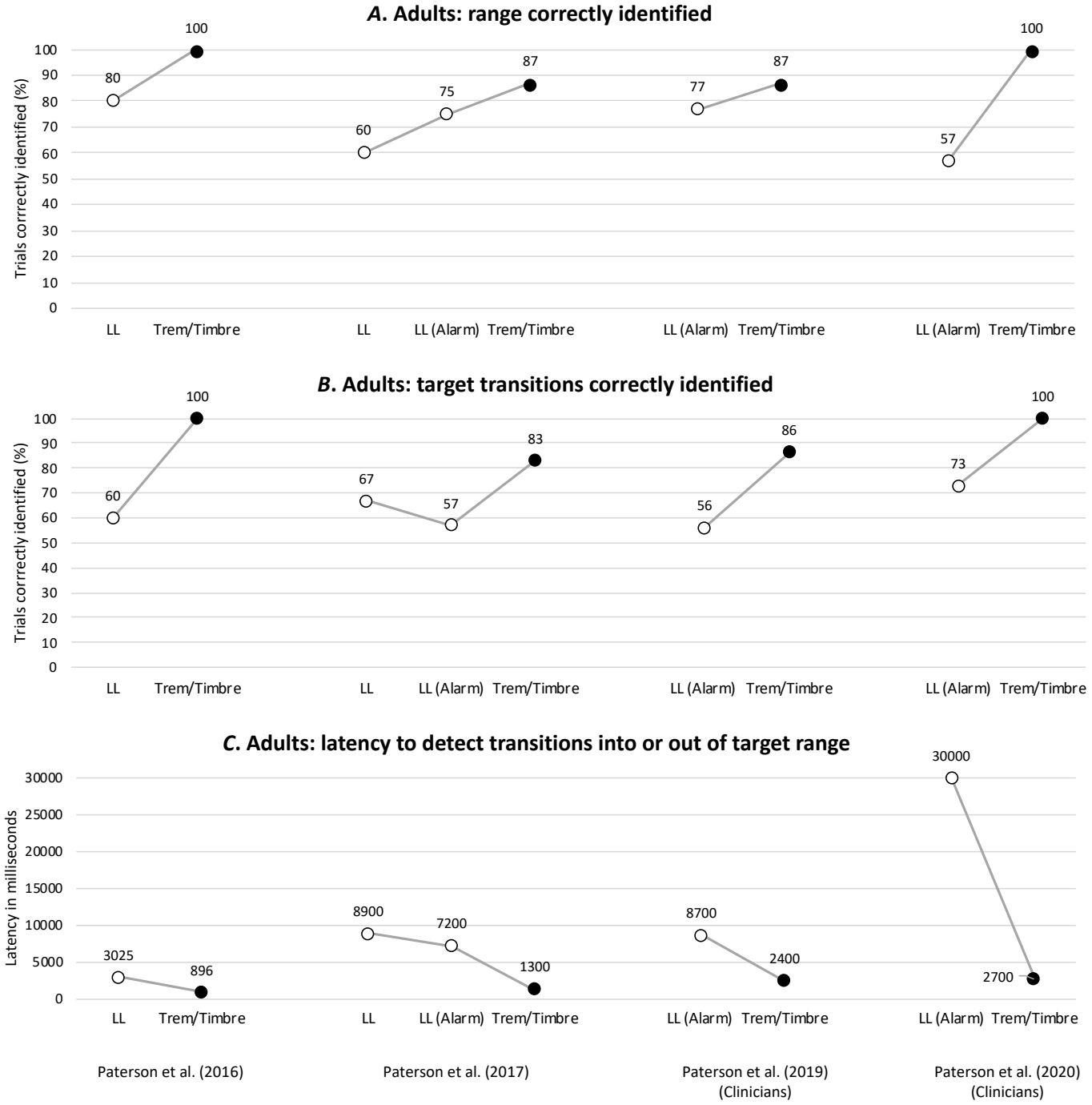

Figure 4. Illustration combining the findings of four studies investigating the impact of discrete acoustic enhancements on participants' judgment of adult pulse oximetry tones.[34–37] LL refers to the loglinear mapping of peripheral oxygen saturation (SpO_2) to tone frequency (in Hz); all conditions used a loglinear mapping. White circles represent control conditions and black circles enhanced conditions. In all studies, performance in the enhanced conditions was significantly better compared with the control conditions. Abbreviation used: trem, tremolo.

Anderson and Sanderson[44] showed that changes in two or more acoustic dimensions can either reinforce or interfere with each other, depending on how they are mapped to parameters such as vital signs. Therefore, enhancing both pulse oximetry parameters or integrating a third vital sign would require careful design and evaluation.

Conclusion

The current variable-pitch pulse oximeter tone is already a powerful auditory display of clinically important information; therefore, altering it may seem superfluous. However, enhancing the variable-pitch tone to convey clinically relevant ranges and desaturation events can improve healthcare providers'

ability to provide safe and effective care. Research has demonstrated substantial improvements in listeners' ability to detect clinical ranges, detect transitions into and out of the target range and other ranges, and identify absolute SpO_2 levels—all without negatively affecting the ability to perform time-shared tasks.[37] Moreover, during the COVID-19 pandemic, when personal protective equipment can restrict clinicians' ability to scan visual displays, the need for effective auditory displays is more important than ever.

Manufacturers should consider providing a means for clinicians to distinguish SpO_2 ranges with simple acoustic enhancements to the variable-pitch pulse oximetry tone. The enhancements should differentiate whether SpO_2 is above (where relevant) or below target, and to what degree, using discrete acoustic signatures for different ranges rather than smooth incremental changes across values. We envision that these ranges would be adjustable by clinicians, who would tailor them for individual patients just as they do for alarm thresholds.

Acoustic enhancements are effective in the absence of alarms, potentially reducing contributions to alarm fatigue, but alarms could still sound at selected levels if and as required. Acoustic features such as beacons, changes in timbre, tremolo, or formants could be used as enhancements, and they yield substantial benefits compared with other approaches, such as manipulating pitch step sizes or specialized training. Further, no intellectual property rights would be infringed—the concept is in the public domain. The sounds required can be adequately reproduced on the sound systems in most commercial pulse oximetry systems in use today. The enhancements suggested could avoid misinterpretations of the pulse oximetry signal that others have documented,[12,15] improve accuracy and timeliness of SpO_2 interpretation, and further reduce the workload of clinicians.

Disclosures

P.M.S. is coinventor of a respiratory sonification (Sanderson and Watson; U.S. patent 7070570). R.G.L. has received $1,000 per year to be on the Masimo, Inc., Scientific Advisory Board.

Funding

Funded by the Australian Research Council (through Discovery Project grants DP140101822 and DP170102611) and the Australian and New Zealand College of Anaesthetists (grant S18/003 to E.P.).

Acknowledgments

The authors acknowledge researchers who conducted studies of pulse oximetry sonification for honors or course credit (Marie-Lys Deschamps, Caitlin Browning, Sam Leav, and Hugh Clarke from The University of Queensland), software engineers (Birgit Brecknell and Ismail Mohamed from The University of Queensland), and collaborators who assisted with the simulation study (Neil Paterson from Queensland Children's Hospital and Isaac Salisbury, Felicity Burgmann, Thomas Davidson, and Garry Mann from The University of Queensland).

References

1. Pedersen T, Nicholson A, Hovhannisyan K, et al. Pulse oximetry for perioperative monitoring. *Cochrane Database Syst Rev*. 2014(3):CD0021013.
2. Moller JT, Johannessen NW, Espersen K, et al. Randomized evaluation of pulse oximetry in 20,802 patients. II: Perioperative events and postoperative complications. *Anesthesiology*. 1993;78(3):445–53.
3. Moller JT, Pedersen T, Rasmussen LS, et al. Randomized evaluation of pulse oximetry in 20,802 patients. I: Design, demography, pulse oximetry failure rate, and overall complication rate. *Anesthesiology*. 1993;78(3):436-44.
4. New WJ, Corenman JE, inventors; Nellcor Puritan Bennett LLC, assignee. Pulse oximeter monitor. US patent 4,653,498. 1986.
5. Miyasaka K, Shelley K, Takahashi S, et al. Tribute to Dr. Takuo Aoyagi, inventor of pulse oximetry. *J Anesth*. 2021;35(5):671–709.
6. Dubus G, Bresin R. A systematic review of mapping strategies for the sonification of physical quantities. *Plos One*. 2013;8(12):e82491.
7. ISO 80601-2-61:2019. *Medical electrical equipment—Part 2-61: Particular requirements for basic safety and essential performance of pulse oximeter equipment*. Geneva, Switzerland: International Standards Organization.

8. Craven RM, McIndoe AK. Continuous auditory monitoring: how much information do we register? *Brit J Anaesth*. 1999;83(5):747–9.

9. American Society of Anesthesiologists. *Standards for Basic Anesthetic Monitoring*. Schaumburg, IL: American Society of Anesthesiologists; 1986.

10. Goldman JM, Robertson FA. Pulse-OX tone conveys vital information. *APSF Newsletter*. 2004;19(2):20–3.

11. Stoelting RK. ASPF stresses use of audible monitor alarms. *ASA Newsletter*. 2004;68(6):25–6.

12. Schulte GT, Block FE. Can people hear the pitch change on a variable-pitch pulse oximeter? *J Clin Monitor*. 1992;8(3):198–200.

13. Santamore DC, Cleaver TG. The sounds of saturation. *J Clin Monit Comput*. 2004;18(2):89–92.

14. Loeb RG, Brecknell B, Sanderson PM. The sounds of desaturation: a survey of commercial pulse oximeter sonifications. *Anesth Analg*. 2016;122(5):1395–403.

15. Morris RW, Mohacsi PJ. How well can anaesthetists discriminate pulse oximeter tones? *Anaesth Intensive Care*. 2005;33(4):497–500.

16. Perez ER, Jimenez E, Albo C, et al. Are anesthesiology providers good guessers? Heart rate and oxygen saturation estimation in a simulation setting. *Anesthesiol Res Pract*. 2019;2019:5914305.

17. Stevenson RA, Schlesinger JJ, Wallace MT. Effects of divided attention and operating room noise on perception of pulse oximeter pitch changes: a laboratory study. *Anesthesiology*. 2013;118(2):376–81.

18. Chandra D, Tessler MJ, Usher J. Audio spectrum and sound pressure levels vary between pulse oximeters. *Can J Anesth*. 2006;53(1):26–32.

19. Deutsch D. *The Psychology of Music*. New York, NY: Academic Press; 2013.

20. Schlesinger JJ, Stevenson RA, Shotwell MS, Wallace MT. Improving pulse oximetry pitch perception with multisensory perceptual training. *Anesth Analg*. 2014;118(6):1249–53.

21. Soong C, Shojania KG. Education as a low-value improvement intervention: often necessary but rarely sufficient. *BMJ Qual Saf*. 2020;29(5):353–7.

22. Stevens SS, Volkmann J, Newman EB. A scale for the measurement of the psychological magnitude pitch. *J Acoust Soc Am*. 1937;8(3):185–90.

23. Brown Z, Edworthy J, Sneyd JR, Schlesinger J. A comparison of linear and logarithmic auditory tones in pulse oximeters. *Appl Ergon*. 2015;51:350–7.

24. Hinckfuss K, Sanderson P, Loeb RG, et al. Novel pulse oximetry sonifications for neonatal oxygen saturation monitoring: a laboratory study. *Hum Factors*. 2016;58(2):344–59.

25. Askie LM, Darlow BA, Finer N, et al. Association between oxygen saturation targeting and death or disability in extremely preterm infants in the neonatal oxygenation prospective meta-analysis collaboration. *JAMA*. 2018;319(21):2190–201.

26. Deschamps ML, Sanderson P, Hinckfuss K, et al. Improving the detectability of oxygen saturation level targets for preterm neonates: a laboratory test of tremolo and beacon sonifications. *Appl Ergon*. 2016;56:160–9.

27. Hinckfuss K. *Using sonification to improve monitoring of oxygen saturation of premature neonates receiving oxygen support* [MPhil thesis]. Queensland, Australia: The University of Queensland; 2018.

28. Dawson JA, Kamlin CO, Vento M, et al. Defining the reference range for oxygen saturation for infants after birth. *Pediatrics*. 2010;125(6):e1340–7.

29. Zestic J, Brecknell B, Liley H, Sanderson P. A novel auditory display for neonatal resuscitation: laboratory studies simulating pulse oximetry in the first 10 minutes after birth. *Hum Factors*. 2019;61(1):119–38.

30. Clarke H. *Novel neonatal pulse oximetry: monitoring oxygen saturation and heart rate in the first mnutes of life* [BA(Hons) thesis]. Queensland, Australia: The University of Queensland; 2021.

31. Janata P, Edwards WH. A novel sonification strategy for auditory display of heart rate and oxygen saturation changes in clinical settings. *Hum Factors*. 2013;55(2):356–72.

32. Schwartz S, Ziemer T. A psychoacoustic sound design for pulse oximetry. *25th International Conference on Auditory Display (ICAD 2019);* 23–27 June; Newcastle-upon-Tyne, UK; 2019.

33. Shepard RN. Circularity in judgments of relative pitch. *J Acoust Soc Am*. 1964;36(12):2346–53.

34. Paterson E, Sanderson PM, Brecknell B, et al. Comparison of standard and enhanced pulse oximeter auditory displays of oxygen saturation:

a laboratory study with clinician and nonclinician participants. *Anesth Analg*. 2019;129(4):997–1004.

35. Paterson E, Sanderson PM, Paterson NA, et al. The effectiveness of pulse oximetry sonification enhanced with tremolo and brightness for distinguishing clinically important oxygen saturation ranges: a laboratory study. *Anaesthesia*. 2016;71(5):565–72.

36. Paterson E, Sanderson PM, Paterson NAB, Loeb RG. Effectiveness of enhanced pulse oximetry sonifications for conveying oxygen saturation ranges: a laboratory comparison of five auditory displays. *Br J Anaesth*. 2017;119(6):1224–30.

37. Paterson E, Sanderson PM, Salisbury IS, et al. Evaluation of an enhanced pulse oximeter auditory display: a simulation study. *Br J Anaesth*. 2020;125(5):826–34.

38. Collett R, Salisbury I, Loeb RG, Sanderson PM. Smooth or stepped? Laboratory comparison of enhanced sonifications for monitoring patient oxygen saturation. *Hum Factors*. 2020;62(1):124–37.

39. Loeb RG, Fitch WT. A laboratory evaluation of an auditory display designed to enhance intraoperative monitoring. *Anesth Analg*. 2002;94(2):362–8.

40. Seagull JF, Wickens CD, Loeb RG. When is less more? Attention and workload in auditory, visual, and redundant patient-monitoring conditions. *Proceedings of the Human Factors and Ergonomics Society 45th Annual Meeting*. 2001;45(18):1395–6.

41. Chima RS, Ortega R, Connor CW. Melodic algorithms for pulse oximetry to allow audible discrimination of abnormal systolic blood pressures. *J Clin Monit Comput*. 2014;28(6):597–603.

42. Burdick K, Bell A, McCoy M, et al. Using multisensory haptic integration to improve monitoring in the intensive care unit. *Audit Perception Cogn*. 2019;2(4):188–206.

43. Burdick KJ, Jorgensen SK, Combs TN, et al. SAVIOR ICU: sonification and vibrotactile interface for the operating room and intensive care unit. *J Clin Monit Comput*. 2020;34(4):787–96.

44. Anderson JE, Sanderson P. Sonification design for complex work domains: dimensions and distractors. *J Exp Psychol Appl*. 2009;15(3):183–98.