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A comparison of linear and logarithmic auditory tones in pulse oximeters

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ABSTRACT

This study compared the ability of forty anaesthetists to judge absolute levels of oxygen saturation, direction of change, and size of change in saturation using auditory pitch and pitch difference in two laboratory-based studies that compared a linear pitch scale with a logarithmic scale. In the former the differences in saturation become perceptually closer as the oxygenation level becomes higher whereas in the latter the pitch differences are perceptually equivalent across the whole range of values. The results show that anaesthetist participants produce significantly more accurate judgements of both absolute oxygenation values and size of oxygenation level difference when a logarithmic, rather than a linear, scale is used. The line of best fit for the logarithmic function was also closer to x = y than for the linear function. The results of these studies can inform the development and standardisation of pulse oximetry tones in order to improve patient safety.

1. Introduction

Pulse oxmietry is widely used in medicine. Pulse oximeters monitor arterial oxygen saturation, which is the percentage of arterial haemoglobin that is fully saturated with oxygen (SpO_2), by transmitting red and infrared light through the finger, where it is sensed. When the SpO_2 is high, haemoglobin is saturated with oxygen, whereas a low SpO_2 refers to the converse. Oxygenation in the patient is a function of baseline oxygenation, metabolic requirement for oxygen (increased in critical illness), ability to utilize oxygen (mitochondrial impairment in sepsis), and cardiac output (the ability for the heart to pump blood throughout the body). Pulse oximetry is an important tool for the anaesthetist as it aids rapid identification of decreased oxygen saturation within a patient, and may reduce critical events in patients undergoing general anaesthesia (Cote et al., 1988; Morris and Montano, 1996; Runciman et al., 1993).

The oxygen-haemoglobin dissociation curve stipulates the oxygen saturation of haemoglobin at a given arterial partial pressure of oxygen. Variables that affect the rightward or leftward shift of this curve include, but are not limited to: temperature, pH, and 2,3-diphosphoglycerate. The sigmoidal shape of the curve possesses the steepest portion of the curve at 90% oxygen-haemoglobin saturation (Cain, 1986; Wang et al., 2011). Thus, a practitioner first noticing that the SpO_2 is 90% and falling forces reactive instead of proactive clinical practice. In the absence of reasons for baseline hypoxemia, such as intrinsic or obstructive lung disease, practitioners are classically taught to take notice when the SpO_2 is between 92 and 94% to follow the trend (ideally) towards 98–100% or to respond to ameliorate the deleterious effects of hypoxemia such as cardiac arrest. However, there is a time lag for the pulse oximeter to detect hypoxemia. Since blood is oxygenated (or not oxygenated, for that matter) in the lungs, it takes time for oxygen-depleted blood to reach the finger where the pulse oximetry probe is placed. The time is a function of cardiac output (heart rate multiplied by stroke volume [the amount of blood systemically pumped with every left ventricular systolic contraction]) and the vasomotor tone of the peripheral vasculature (Cain, 1986; Wang et al., 2011; Wright, 1992). This time lag, worsened in low cardiac output states, can cause late detection of hypoxemic events and cause practitioners to doubt if an endotracheal tube is correctly placed in the trachea, or incorrectly placed in the oesophagus. Therefore, co-monitoring with capnography (carbon dioxide) detection is used by practitioners.

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Because hypoxemia can have irreversible and deleterious neurological outcomes, a practitioner must form a differential diagnosis and respond quickly and accurately. Practitioners assess hypoxemia by working from “patient-to wall” or from “wall-to-patient.” It is imperative to assess the oxygen supply to the patient including, but not limited to: pipeline pressure supply, oxygen availability, functioning inspiratory and expiratory valves, and oxygen sensor (Cain, 1986; Pierson, 2000). Then, the practitioner will assess the delivery method to the patient via facemask or advanced airway device to ensure that inspired oxygen is being delivered in the trachea. Finally, the practitioner will assess patient reasons for hypoxemia including, but not limited to: pneumonia, pulmonary embolus, anaemia, acute respiratory distress syndrome, chronic obstructive pulmonary disease, interstitial lung disease, pneumothorax, pulmonary oedema, and sleep apnoea. These clinical entities may be acute, chronic, acute-on-chronic, and may or may not have actionable intervention implications for the practitioner. Thus, the practitioner is usually fairly busy when acting upon an adverse, or potentially adverse, SpO_2 reading.

The use of a simple sonification (turning data into sound in a meaningful manner), where the pitch of the auditory tone changes with the level of oxygen saturation, was a relatively early design advance in pulse oximetry initially introduced by the Nellcor Corporation in 1983. The principle of this sonification is that, as oxygen saturation rises, so does the frequency of the tone used to indicate a change in saturation level. Subsequent research on variable pitch pulse oximeters indicated that most users were able to perceive this pitch change, and that the speed of response of the anaesthetist was reduced in comparison with a fixed-tone oximeter (Schulte and Block, 1992; Craven and McIndoe, 1999). Since trainees in anaesthesiology learn to monitor patients with variable pitch pulse oximetry, trainees develop a reflexive response when “beep” turns to “boop; ” that is during the transition of oxygen-haemoglobin desaturation. The variable tone pulse oximeter has set itself apart by allowing for unisensory auditory clinical information in the form of heart rate (tempo), oxygen-haemoglobin saturation (pitch), rhythmicity of the heart (regular or irregular tone), and even blood pressure (distal perfusion Is required to generate an output signal). Sonification beyond simple pulse oximetry has also been demonstrated to be useful in the anaesthesia environment (Watson and Sanderson, 2004, 2007).

Given the apparent usefulness of the variable-tone pulse oximeter, it is interesting that the nature of the variability in tone, and indeed the tones themselves, vary enormously across devices. A review of some extensively-used pulse oximeters (Chandra et al., 2006) demonstrated that change in saturation levels was universally indicated by a change in tone, but there the similarity ended. Chandra et al. found that some were louder than others, some produced a greater loudness range, and analysis of the spectrum revealed considerable variation in the harmonic content and complexity of the tones used. They also found variation both in the absolute pitch of the tones used and the way pitch varied as a result of changes in saturation. For example, the pitches of the tones indicating 85% saturation ranged from 375 to 844 Hz, 90% from 422 to 938 Hz and 99% from 469 to 1078 Hz. Other studies have revealed similar variation (Santamore and Cleaver, 2004). Both Chandra et al. and Santamore and Cleaver suggest that this variation is likely to cause problems for anaesthetists when moving from one pulse oximeter to another.

Studies which have surveyed the audible tones used in pulse oximetry also highlight the fact that the degree and nature of the frequency change with change in saturation varies across oximeters. Santamore and Cleaver's study showed that the change in frequency per degree of saturation ranged from 4 to 21 Hz, and that the difference between 95% and 100% saturation levels in some cases covers a pitch range of a single semitone, which is the smallest unit of difference on a piano (for example, between a white key and the nearest black key). Whilst we know that the smallest perceptible difference between tones necessary in order to hear a difference in pitch is about 1/12 of a semitone (the Just Noticeable Difference (JND) (Weber, 1834)) this level of discrimination is recorded from laboratory experiments, in quiet conditions, and where the listener is neither stressed nor carrying out a secondary task, none of which is true of the working environment in which pulse oximetry tones will typically be heard. Indeed, Schulte and Block's finding (1992) suggest that the direction of change is typically detectable only about 2/3 of the time by anaesthetists using oximeters which use these small frequency changes.

Another important issue concerning the relationship between the audible tones used and the saturation levels which they represent is that, for the majority of pulse oximeters, the mapping between saturation change and frequency change is linear (Santamore and Cleaver, 2004). For example, some of the Datex oximeters showed a change of approximately ten hertz per degree of saturation, regardless of the saturation value being represented. The problem with using linear mappings between saturation change and frequency change is that pitch perception, which is the psychological correlate of the physical entity of frequency, is logarithmic rather than linear in nature. Differences in pitch which sound equivalent to the listener are based on fixed proportions rather than fixed numbers. For a difference in pitch between any two tones to be judged as equivalent, the increase in frequency must be the same proportion of the two frequencies. For example, for three octaves to be regarded as being successive octaves apart their frequencies (if the first one was 200 Hz) would be 200 Hz, 400 Hz and 800 Hz (doubling the frequency for each octave in the ratios 1:2:4) rather than 200, 400 and 600 Hz (ratios of 1:2:3). For the semitone, which is the smallest unit of pitch difference typically used in music (represented by two adjacent piano keys) the change in frequency from one tone to another a semitone higher is approximately equivalent to {(first frequency)*twelfth root of two} (Helmholtz, 2009). Thus, the higher the first tone, the greater the change in Hz required to produce a tone which is perceptually a semitone higher. This means that the higher the oxygen saturation, the smaller becomes the difference in pitch between similar percentage changes.

Morris and Mohacsi (2005) played the tones used in a Datex AS/3 pulse oximeter to anaesthetists and found that while anaesthetists were generally able to judge lower saturation levels as being lower than higher ones, the estimates of the actual saturation level represented by the tones was very compressed, so that the median perceived estimates for 70% saturation was 89%. Estimates for 80% saturation were 93%, but correct for 94%. Morris & Mohacsi also played anaesthetists pairs of tones and asked them to estimate the difference in saturation represented by those tones and found that the median estimate of difference between two tones representing a 20% change in saturation was 5%. They also found that as the difference between the two tones was reduced, the ability of anaesthetists to accurately record the direction of change (up or down) declined, with only 70% of direction judgements being correct for the smallest saturation difference presented, 2%. Morris and Mohacsi's data therefore suggests that a linear scale with small frequency differences leads to overestimation at the bottom end of the saturation scale, and underestimation of saturation change when two tones are presented in close temporal proximity, as well as lack of clarity of direction change with smaller saturation differences.

Morris and Mohacsi suggest that the use of a non-linear scale, such as a semitone scale, may prove more effective and should be