What is a Good Wearable Medical Alarm Design, Anyway?

Do we really know to design a wearable medical alarm?

Horia-Nicolai Teodorescu[1,2]
[1] 'Gh. Asachi' Technical University of Iasi
[2] Institute of Computer Science of the Romanian Academy
Iasi, Romania
hteodor@etti.tuiasi.ro

2021 International Conference on Applied Electronics (AE) | 978-80-261-0973-0/21/$31.00 ©2021 10.23919/AE51540.2021.9542891

Abstract – **Designing alarms for medical equipment may seem easy, but the standards' requirements combined with the nonlinearity of the acoustic transducers, with the difficulties of assessing the acoustic impedance of the transducer chamber, and with criteria such as power consumption and efficiency of the electric to acoustic conversion make the design challenging. We systematically analyze the related problems and discuss design solutions specifically for wearable alarms; examples are shown for an implemented alarm with usual driver. The main focus is on the power efficiency and the sound spectra of these alarms.**

Keywords-medical alarm; wearable device; telemedicine; driving circuit; spectra; acoustic transducer; standards

I. INTRODUCTION

With the increased use of wearables, the need for easy to recognize and power-efficient sound alarms has vastly expanded. Wearable alarms have to be heard in various ambient conditions, some of them involving large noise, yet in some cases such as airplane cockpits or roads the dangers announced by the alarms may require immediate attention. Also, in many hospital ambient cases, there are loud noises that may distract, yet the alarms have to attract immediate attention. On the other hand, the design of alarms for wearables is restrained by power considerations. This study aims to contribute design considerations that may lead to improved designs for medical alarms, especially for wearable equipment where energy consumption and efficiency are issues.

Medical alarms may save lives. According to the literature, poor recognition of medical alarms leads to hundreds of deaths. The main features of alarms for medical use are audibility and recognition (discrimination) rate, among other alarm sounds [1-3]. Studying in 2007 a set of 23 auditory alarms used in the intensive care unit (ICU) and 26 auditory alarms in the operating rooms (ORs), [1] found that alarms can be easily "*masked by the sound of a surgical saw or a surgical drill*" and by the sounds of other alarms. In [1], 10 to 15 (out of 26) alarms were identified by anesthetist workers in ORs, while between 9 and 14 (out of 23) alarms were identified by ICU nurses.

The design of medical alarms is deceivingly simple: all needed is a generator of impulse trains, a buzzer, and a transistor driving the buzzer. Yet, such designs almost always will not satisfy the standards and may have a ridiculously poor efficiency. Even in applications where alarms are critical and power consumption is an issue, such as a guiding cane for blind people as in [4] and [5], or water detection for people with similar disabilities ("*activates a distinct buzzer if it detects water*") [6], [7], no consideration was given to the alarm design.

The standards for acoustic alarms refer to sound intensity, spectral components, and waveforms. Essentially, the standards require a basic frequency of less than 1 kHz and 4 harmonics with frequencies between 300 Hz and 4 kHz (within ± 15 dB of the fundamental frequency component).

Paraphrasing the standard IEC 60601-1-8 [8] and the literature, the requirements for medical alarms include: (i) independent signals for sound and light alarms; (ii) different sounds and lights for different alarm priority levels; (iii) gradual increase and decrease of the sounds; (iv) at least 4 harmonics in the bandwidth from 300 Hz to 4 kHz, ± 15 dB from the fundamental, for avoiding 'mute spots' in a room, where interferences at a given wavelength may dump the sound at a certain frequency; (v) two simultaneous alarms should not reciprocally mask each other, in the acoustical physiology sense; (vi) very high accuracy of alarm occurrences: false positives and false negatives should be extremely rare.

One of the major matters considered when standardizing and designing alarms of medical use is the masking of concurrent alarms [2], [9] and environment noise, but there are several other considerations. Edworthy et al. [10-14] found issues including that "*The audible alarms associated with IEC 60601-1-(2012) ... are difficult to learn and retain*" and that the recognizability and localizability of auditory alarms according to that standard were outperformed by "alternative sets of alarms conceived as 'auditory icons'. Notice that the standard has an "amendment 2" issued in 2020, adding "*reserved melodies for alarm signals*", and an annex (H, informative) on validation of auditory icons; yet, I believe these additions have not changed much of what Edworthy et al. [10-14] found.

In an early paper, Block et al. [15], citing a study of 1993, mentions that anesthesiologists are 50-50% split about coding the alarm sounds by type of device generating them, or by the organ that needs immediate attention. These authors also support alarms

ISBN 978-80-261-0973-0, © University of West Bohemia, 2021

represented by melodies that are easy to memorize. Takeuchi et al. [16] proposed a package of alarm sounds for further study and adoption as alarms, but there was no conclusive choice in their study. Sessa [17] also analyzes the standard IEC 60601-1-8 (2006) and proposes a set of alarms based on melodies and musical pitches between c and C (one octave above c). Replacing simple sounds with melodies in wearables is prone to further reduce their power efficiency and complicate the design. However, none of the papers [1-3] and [8-17] put forward clear requirements for the instantaneous spectra of the melodies, or discussed the power efficiency of the alarms.

II. MATTERS WITH THE CURRENT STANDARDS IN CHOOSING THE ALARM SIGNALS

The designer has limited control of the actual audio spectrum generated because the low cost sound transducers are nonlinear, especially the magnetic ones, and they intentionally produce – because of the standards for medical alarms – a large number of strong harmonics.

The literature includes technical documentations such as [18] that may help developing alarms in accordance with the IEC 60601-1-8. Recognizing the difficulties of producing a good, standard-compliant medical alarm, an alarm system (TIDA-010040) was commercially introduced [18]; it has a complex block diagram with two microcontrollers and several amplifiers and multiplexers. This alarm system is, however, very complex, expensive, has a large board, and is power hungry. Fig. 24 in [18] shows that two harmonics are in the range of 10 dB, 3 in range of 15 dB and 4 in the range of 20 dB from each other, for a high-priority burst with 260 Hz base frequency. Similar results are shown in [18] for a medium-priority burst based on 260 Hz. However, those signals are at the output of the electronic board, *not* audio signals. A perfect – but bulky and expensive – loudspeaker is needed to obtain audio results replicating the electrical signals.

Several questions arise from the standards and the manufacturers' datasheets for alarms and buzzers. Standards for medical alarms leave the liberty of choosing the duration of the pulse trains but do not elucidate the effect of the pulse train duration on the spectrum of the signal. Also, the standards leave opened the frequency of the control (fundamental) signal, with no indication on the effect of this frequency on the spectrum.

Spectra that are good, from the point of view of the specification of the standards, for continuous wave or train excitation do not guarantee good results for short impulse trains. In fact, for short pulse trains, the transducer and the entire circuit may operate largely in a transitory regime, see Section IV.

Another issue not clarified by the standards is on what time interval (window) the spectra should be determined and how to place that window on the signal, for example at its middle or at the beginning of a burst of impulses. The width and position of the window certainly affects the determined spectrum.

III. ISSUES RELATED TO THE SPECTRUM

The standards do not impose any constraints on the waveforms of the control (excitation) of the buzzers, only on the resulted sounds. This leaves the designer much liberty in changing the waveform, from the 50-50% ratio recommended by most buzzer manufacturers to other duty cycles. Improving the medical alarms, in terms of spectrum and of overall efficiency, by manipulating the buzzer command waveforms is a possibility for the designer.

Being given the signal generated by the synthesizer, $s(t)$, with a spectrum $S(\omega)$, the function $f\left(s(t)\right)$ of the transducer, and the characteristic of the resonating chamber of the transducer, including openings, $H_r(\omega)$, the spectrum $F\left(f\left(s(t)\right)\right)$ produced by the transducer produces a signal with the spectrum $S'(\omega) = F\left(f\left(s(t)\right)\right) H_r(\omega)$. When, according to the standards, only four harmonics between 300 Hz and 4 kHz count, the power of all the other harmonics is a waste of power for the circuit. Even when considering the required four harmonics, when their bandwidth is too large in the generated spectrum, the part of their energy corresponding to frequencies not close enough to the required harmonics may be considered wasted.

The magnetic and electromagnetic transducers, as named by several manufacturers, are devices that generate sounds using two coils or a coil and a permanent magnet, moreover have no internal circuit, thus leaving choice to the designer in trimming a circuit to the sound generator. These devices are frequently named buzzers in applications. Unfortunately, the manufacturers do not clarify the influence of the duty cycle of the driving signal, yet the spectrum of the command signal depends much on the duty cycle. For example, for 50% (square wave), the spectrum is shown in Fig. 1(a), for 25% in Fig. 1 (b), and for 85% in Fig. 1(c). Notice that the last case is the best, contrary to the recommendations of several datasheet from different manufacturers.

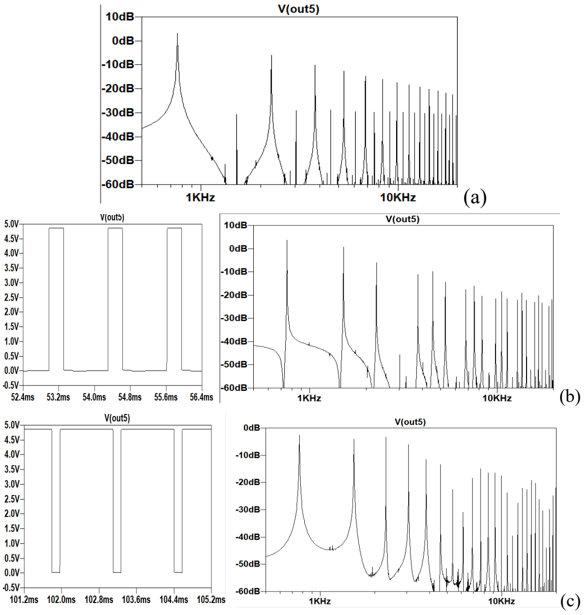

Figure 1. Examples of changes in the spectrum of the command signal with the width of the pulses

Therefore, we recommend that the design investigates the usefulness of several duty cycle values for homogenizing the spectrum (bringing the four required harmonics to closer amplitudes) and for reducing the higher harmonics for reasons explained in Section IV. However, the change in the duty cycle for improving the spectrum in agreement with the standard is not always possible because it also changes the sound intensity at constant power supply. Increasing or decreasing the current through the driver and the sounder for maintaining the power constant on them when the duty cycle is modified is a solution. The designer has to tradeoff sound intensity and sound spectrum, yet keeping both according to the standard.

Some companies define the frequency response curve of a buzzer by measuring it at 10 cm in front of the sound generator, both at 40 cm from the ground, under very specific conditions, namely a square wave with 50% impulse, fixed frequency and fixed amplitude excitation [19]. On the other hand, the measuring distance and the environment affect the spectrum. Moreover, the decrease in intensity is not according to the geometrical attenuation, when the environment is more complex. In addition, this method of testing is different from that of loudspeakers. All these may indicate that the requirements of the current standards and the firms' measuring recommendations may be still inadequate.

IV. THE EFFICIENCY

A literature search found no study dealing with the efficiency of sound alarms. No paper was found in IEEExplorer with the keywords "driver buzzer efficiency" or with "buzzer driver efficiency". There are 44 papers found with the keywords "buzzer driver", 18 for "buzzer efficiency" but not dealing with the topics in this study, 19 for "audio alarm efficiency" – vast majority unrelated to power efficiency. None of the above papers dealt with the actual design of the alarm.

A. Effect of the circuit and transducer

The magnetic transducers have basically an RL equivalent series circuit (Fig. 1), with the active element converting the electric power into sound being the inductance. The parallel resistor R_{1p} stands largely for the emitted power. Some part of the energy dissipation and thus of the equivalent resistance is due to dissipation in the membrane, which is conductive. The spectrum of the driving signal affects significantly the efficiency, as the losses increase with the frequency. Higher frequencies may be converted with lower efficiency into sounds. Any mismatch between the main spectral component of the signal and one of the resonances of the transducer also significantly decreases the alarm circuit efficiency.

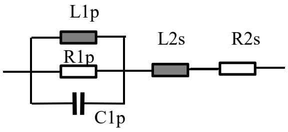

Figure 2. An equivalent scheme, according to Fig. 1 in [20]. R_{1p} is stands in this model for the radiated sound power.

B. The electric efficiency

In a project similar to the one described in [21] and [22], the power consumption of a buzzer is not negligible; for example the buzzer CMT-1271-88-SMT-TR [22], which is a magnetic buzzer transducer has the "*current consumption at rated voltage, 2,400 Hz, ½ duty square wave 40 mA*". It produces a minimum of sound pressure level at 10 cm, rated voltage, 2,400 Hz, ½ duty square wave, 88 dB. The buzzer has a coil resistance of 40Ω to 50Ω. The recommended circuit is a common emitter transistor with a 180Ω resistor in the base. Similar features are found for other magnetic sounders, e.g. [18], [19]. The power efficiency ρ_{Alarm} of the magnetic alarm circuits is approximately $\rho_{Alarm} = \frac{R_{emit} I_C}{I_C(U_{CE}+R_{buz} I_C)+(V_{CC} I_B)}$, where $R_{emit} \approx R_{2p}$.

The simulation of the circuits with magnetic buzzers is especially difficult because the lack of models from the manufacturers. In comparison, several models for Spice can be found for piezo buzzers. Roughly, with 43 Ω in the collector (resistance of the transducer/buzzer), $I \approx V_{DC}/(40 \cdots 50) \approx 120 \ldots 100\, mA$, which, for a square wave pulse means 50···60 mA, assuming a low frequency where the inductance does not count. At 1 kHz, with the inductance of 5 mH, $X_L = 2\pi f L \approx$ 35Ω. The current at 1 kHz is then about 20…25 mA for a pulse width of 50%. The power per alarm burst of pulses of 250 ms is $W = UIt \approx 0.072\, W$. In addition, the base resistor in the recommended circuit is of low value, 180 Ω, adding about $\frac{35}{180} \approx 20\%$ power consumption to that of the collector, with a total of $0.072 \times 1.2 = 0.086\, W$. For three pulses (medium priority alarm as per the standard) this means about 0.258 W. Repeating the alarm an average of 5 times results in a power consumption of more than 1.2 W, which is not negligible for a wearable. For portables with large batteries, the alarm power consumption may not count. To the consumption of the buzzer and its driving transistor, one should add the power consumption of the microcontroller driving the alarm. The power used by the microcontroller is made of the power used by the output port and the power used by the software section related to the alarm generation

C. The acoustic efficiency

When too many and too large harmonics occur in the driving electric signal spectrum and these harmonics are not corresponding to the frequencies of the buzzer response and/or tor the standards' recommendations, they uselessly consume power. We define the acoustic efficiency as the ratio of the power in the spectral components required by the standards and the total power in the signal. The efficiency of the power consumption by the alarms is low. Consider the power of the theoretical signal in Fig. 1(a) in a band around the main frequency component (in our case, at 800 Hz), where the bandwidth was chosen on 21 frequency components centered on the main frequency (in our case, from 768.75 Hz to 831.25 Hz). The ratio defined as

$$\eta = \sum_{c-10}^{c+10} s_k^2 \Big/ \sum_{k_0}^{k_M} s_k^2, \qquad (1)$$

indicates how efficiently is used the spectrum of the signal according to the standards, where c is the index of the central spectral component, k_0 is the minimal index of the spectral components (in our case, $k_0 = 0$), k_M is the highest index, and s_k are the (absolute) magnitudes of the spectral components. For the discussed (standard medical alarm signal) the ratio is only 0.535, that is $\eta < 54\%$.

We exemplify the issue by the analysis of an alarm implemented with the buzzer CMT 1271-88-SMT-TR driven with a 50% duty cycle impulse train according to the manufacturer specifications. The sound at the middle of an impulse is shown in Fig. 3 and the impulse and its main components (obtained by Praat™) are shown in lower panel of Fig. 3. Fig. 4 shows the spectrum.

A high priority alarm sound recorded for the same device is shown in Fig. 5 and the corresponding spectrum as determined at the middle of a burst (window of 0.04 s) is shown in Fig. 6.

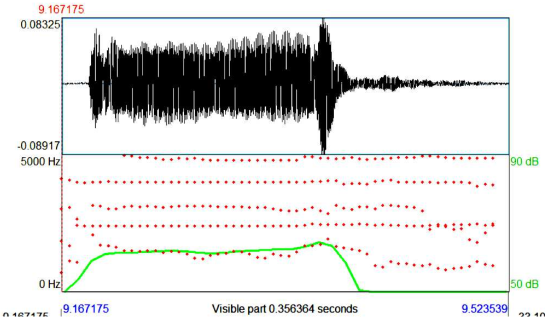

Figure 3. Recorded sound (single burst alarm) and its main spectral components.

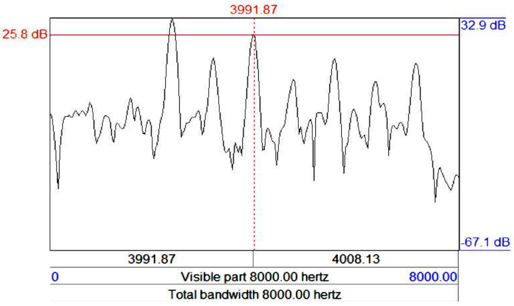

Figure 4. Bursts sound for single burst alarm designed for a portable medical equipment. The fundamental is at 800 Hz.

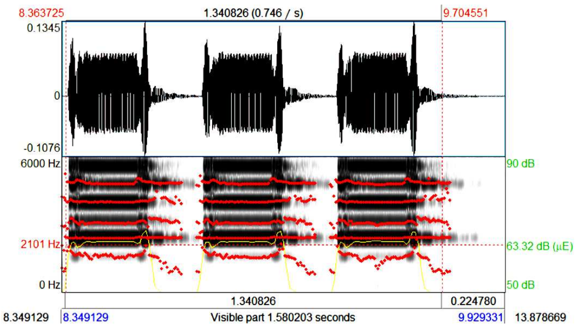

Figure 5. Waveform and main components of the 3-bursts alarm.

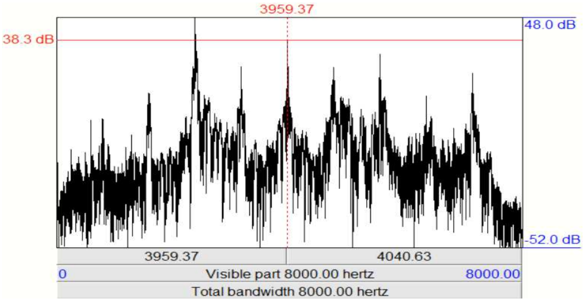

Figure 6. Spectrum of the overall signal (three consecutive bursts)

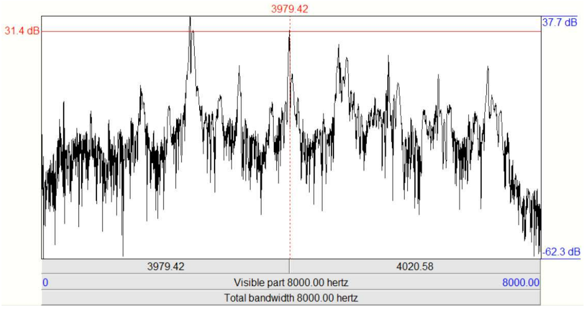

Figure 7. Spectrum for low voltage burst (single burst), There are 20 dB between the peak at 3177 Hz and the peak at 3979 Hz. Notice that for the whole signal of 3 bursts and the one for a single burst, the distances between the main peaks differ, and the whole spectra differ.

As already mentioned, the standards are not clear about how to define the window for determining the spectrum of the signal. In addition, the standards allow for choices of the impulse trains in wide margins. However, the spectra will differ significantly, as expected. For example, for the same circuit, for trains of 10 ms, 100 ms, and 250 ms, the spectra are largely different, see Fig. 6 compared to Fig. 7. There are two reasons for this: a smaller dataset for FFT will have lower frequency resolution, as it entails fewer samples, and, more importantly here, there is a transitory regime at the beginning and the end of each impulse train, and these alter the spectrum with a greater weight for small recordings.

V. DISCUSSION AND CONCLUSIONS

Because the emitted sound spectrum depends much on the segment of the sound where it is measured, the standards should make clear (for now there is no specification) on what time interval the spectrum is defined.

It is illusory to believe that the amplitude of the alarm pulses is constant or defined by the signal generated by the microsystem. Also, it is illusory to think that the harmonics in the audio signal are those in the driving signal, as the articles [17,18] seem to suggest. The amplitude and the entire waveform of the original electrical signal is much modified by the current amplifier, by the transducer and then, at the sound level, by the case of the transducer and the case of the device.

The acoustic efficiency, as a parameter introduced in Section IV, has to be considered in the design of high efficiency alarms. In addition, the electric and the overall efficiency has to be determined and adjusted during the design by appropriately choosing the duty cycle of the driving signal, the sounder, the driving circuit, and the parameters of the case housing the sounder.

For future designs, we suggest that a variable duty cycle with fixed period could help obtaining an equivalent of the amplitude modulation, with possible enhancement of the generated or perceived sound.

Throughout this paper, we discussed results obtained with an alarm essentially based on the elementary circuits recommended in [19], [23], which include one transistor, a base resistor of 180 Ω and a reversed diode. However, the operation of these circuits depends on the transducer and the additional capacitances used in the circuit. The operation may become unstable; for example, simulations of the circuit in Fig. 8(a) detect a chaotic behavior.

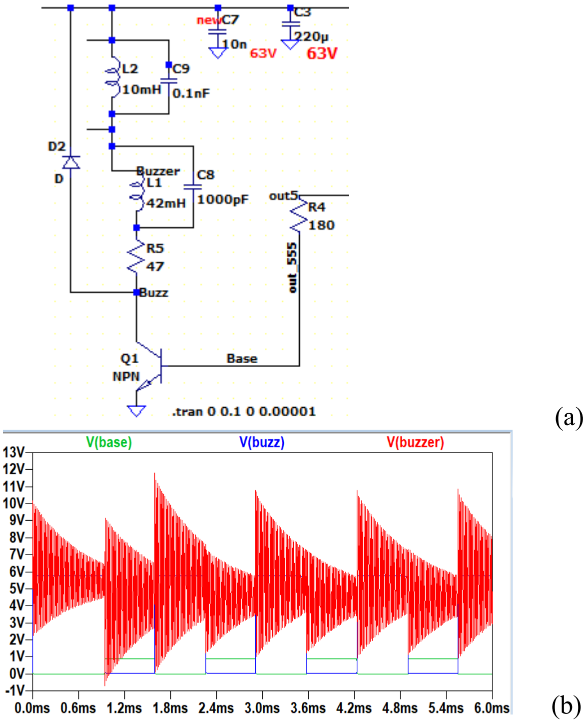

Figure 8. A hypothetical transducer with large inductance and capacitance values may produce a chaotic alarm signal instead of the desired tones.

An intelligent alarm that self-detects the environment, open space or closed space and if open space the proximity of sound reflectors, to adjust its frequency and to determine the efficiency of reflectors and the reverberations could improve the safety of the patients. The most obvious way is to use a 3D camera (time of flight camera) and building a map of the location, then use a noise or a sweeping sound (a chirp) to determine the reverberations and the optimal frequencies for the alarm. A 2D camera and image recognition may also be useful instead of 3D camera.

ACKNOWLEDGMENT

This study was carried out independently by the author and with no financial support from any institution. I thank Mike Teodorescu for the conception and for much of the planning of this study, and for several of the ideas included in this paper; I also thank eng. C. Cojocariu for implementing a design of alarm (according to M. Teodorescu's specifications) and recording the sounds analyzed in Figs. 3-7.

REFERENCES

[1] K. Momtahan, R. Hétu & B. Tansley (1993) "Audibility and identification of auditory alarms in the operating room and intensive care unit," Ergonomics, Vol. 36:10, 1159-1176, DOI: 10.1080/00140139308967986.

[2] B. Hasanain, A. D. Boyd, J. Edworthy, M.L. Bolton, "A formal approach to discovering simultaneous additive masking between auditory medical alarms," Applied Ergonomics, Vol. 58, 2017, pp. 500-514, doi.org/10.1016/j.apergo.2016.07.008.

[3] B. Hasanain, A. D. Boyd and M. L. Bolton, "Using model checking to detect simultaneous masking in medical alarms," in IEEE Trans. Human-Machine Systems, vol. 46, no. 2, pp. 174-185, April 2016, doi: 10.1109/THMS.2014.2379661.

[4] A.T. Noman, M. A.M. Chowdhury, H. Rashid, S. M. Faisal, I. U. Ahmed and S.M. Reza, "Design and implementation of microcontroller based assistive robot for person with blind autism and visual impairment," 2017 20th Int. Conf. Computer and Information Technology (ICCIT), Dhaka, 2017, pp. 1-5, doi: 10.1109/ICCITECHN.2017.8281806.

[5] K. Palaguta, V. Bebenin, and A. Kuznecov, "Testing of the device of the help to visually impaired people for positioning in space," 2019 Int. Seminar Electron Devices Design and Production (SED), Prague, Czech R., 2019, pp. 1-5, doi: 10.1109/SED.2019.8798429.

[6] R.F. Olanrewaju, M.L. Radzi and M. Rehab, "Walk: Intelligent walking stick for visually impaired subjects," 2017 IEEE 4th Int. Conf. Smart Instrumentation, Measurement and Application (ICSIMA), Putrajaya, 2017, pp. 1-4, doi: 10.1109/ICSIMA.2017.8312000.

[7] P. T. Moran, G. F. Harris, K. Acharya, H. Zhu and J.J. Wertsch, "A biofeedback cane system: instrumentation and subject application results," in IEEE Trans. Rehabilitation Eng., vol. 3, no. 1, pp. 132-138, Mar 1995, doi: 10.1109/86.372903.

[8] *** IEC 60601-1-8:2006+AMD1:2012+AMD2:2020 CSV "Medical electrical equipment - Part 1-8: General requirements for basic safety and essential performance - Collateral Standard: General requirements, tests and guidance for alarm systems in medical electrical equipment and medical electrical systems". Edition 2.2 2020-07, Consolidated Version.

[9] P. Lacherez, E. Seah and P. Sanderson, "Overlapping melodic alarms are almost indiscriminable", Human Factors, vol. 49, no. 4, pp. 637-645, 2007.

[10] J. Edworthy, Reid S, McDougall S, et al. "The recognizability and localizability of auditory alarms: setting global medical device standards." *Human Factors*. 2017; Vol. 59 (7), pp. 1108-1127. doi:10.1177/0018720817712004.

[11] J. Edworthy et al., "Getting alarm sounds into a global standard: a case study with reflections." https://core.ac.uk/download/pdf/161510983.pdf Also in Ergonomics in design, Oct. 2018, pp. 4-13.

[12] J. Edworthy; "Designing Effective Alarm Sounds." *Biomed Instrum Technol* 1 July 2011; Vol. 45 (4): 290–294. doi: https://doi.org/10.2345/0899-8205-45.4.290.

[13] J. Edworthy, E. Hellier, 2006, "Alarms and human behaviour: implications for medical alarms." British J. Anaesthesia, Vol. 97 (1), pp. 12–17 (2006), doi:10.1093/bja/ael114.

[14] J. Edworthy, Baldwin C., "Medical audible alarms and IEC 60601-1-8." Proceedings of the Human Factors and Ergonomics Society Annual Meeting. 2016; Vol. 60(1), pp. 634-635. doi:10.1177/1541931213601145.

[15] FE. Block, Rouse JD, Hakala M., Thompson CL, "A proposed new set of alarm sounds which satisfy standards and rationale to encode source information." J Clin. Monit. 2000, vol. 16, pp. 541-546.

[16] A. Takeuchi, Hirose, M., Shinbo, T., M. Imai, N. Mamorita, N. Ikeda, "Development of an alarm sound database and simulator." J Clinical Monitoring and Computing, vol. 20, 317–327 (2006). https://doi.org/10.1007/s10877-006-9037-9.

[17] P. Sessa, “Guidelines for medical alarm system software design.” Altran Italia, Technology Review # 08, pp. 16-27, http://admin.altran.it/fileadmin/medias/IT.altran.it/Images/Publication/TechnologyReview/Technology_Review_n._8_-_Ottobre_2012_P.Sessa.pdf. Accessed March 10, 2021.

[18] *** TI Designs: TIDA-010040. Alarm Tone Generator Reference Design (Dec. 2018, Texas Instruments Incorporated).

[19] Soberton, Buzzers / GT Series / GT-0903A datasheet, https://www.soberton.com/gt-0903a, accessed March 10, 2021.

[20] J.R. Wright, “An empirical model for loudspeaker motor impedance.” J. Audio Eng. Soc. Vol. 38, no. 10, 1990, pp. 749-754.

[21] M. Teodorescu, HN Teodorescu, “An open design for an air flow and pressure control circuit for medical devices,” 2020 International Conference on Applied Electronics (AE), Pilsen, Czech R., Sep 2020, pp. 1-6, doi: 10.23919/AE49394.2020.9232840. Also at https://otik.uk.zcu.cz/bitstream/11025/39928/1/09232840.pdf.

[22] D.L Teodorescu, S. Okajima, A. Moten, M. HM Teodorescu, M. El Hechi et al., “A Paradigm Shift in Critical Care Infrastructure in Complex Settings: Evaluating an Ultraportable Operating Room to Improve Field Surgical Safety.” 2021/1, Military Medicine (J)., Vol. 186 Issue S1, pp. 295-299, Oxford University Press, https://doi.org/10.1093/milmed/usaa311.

[23] *** Magnetic Sounder. https://elmetric.se/wp-content/uploads/2016/06/Technology-Magnetic-Sounder-from-Star.pdf, accessed February 14, 2021.