ORIGINAL ARTICLE

New technical solution to minimise noise exposure for surgical staff: the 'silent operating theatre optimisation system'

Martin G Friedrich,[1] Margarete Boos,[2] Manuela Pagel,[2] Tobias Thormann,[3] Adel Berakdar,[1] Sebastian Russo,[3] Theodor Tirilomis[1]

[1]Department of Thoracic and Cardiovascular Surgery, University Medical Center Göttingen, D 37075 Göttingen, Germany, Robert-Koch-Str. 40
[2]Department of Social and Communication Psychology, University of Göttingen, Georg-Elias-Müller-Institute of Psychology, Göttingen, Germany
[3]Department of Anaesthesiology, Intensive Care and Rescue Medicine, University Medical Center Göttingen, Göttingen, Germany

Correspondence to
Martin G Friedrich, Department of Thoracic and Cardiovascular Surgery, University Medical Center Göttingen, 4037075 Goettingen, Robert-Koch-Str. 40, Germany; m.friedrich@med.uni-goettingen.de

Received 20 December 2016
Revised 9 August 2017
Accepted 8 September 2017

To cite: Friedrich MG, Boos M, Pagel M, *et al*. *BMJ Innov* Published Online First: [please include Day Month Year]. doi:10.1136/bmjinnov-2016-000188

ABSTRACT

The increasing number of technical equipment in the operating room (OR) is resulting in significantly higher noise levels. The more complex and sophisticated the surgical procedure is, the more essential it is for all team members of the OR to work together in a harmonious fashion to process and manage their demanding team tasks. With increasing noise in OR, the risk of more frequent errors also increases. The reduction of noise production in the OR is possible but limited. The aim of this study was to develop a device that reduces ambient noise for the operating team without hindering their ability to communicate.

We developed a new communication technology set-up for the OR to meet all needed requirements. All members of the operating team are issued headsets with microphones. The headsets filter out background noises (active and passive noise cancelling) and the microphones enable interactive communication among and between OR subgroups through targeted information selection (signal selection). Any remaining background noise is overshadowed by music, which is quiesced by direct speech into the microphone (ducking). Information flow is programmed on a digital workstation, providing each team member a selection of acoustic signals from the OR on their bidirectional headset. A complex matrix of connections in this audio technology allows a predefined communication structure. These procedures were assembled in the Silent Operating Theatre Optimisation System (SOTOS). The technical specifications and user interface are described.

A pilot study in 2015 using the SOTOS in cardiac surgery showed very positive feedback from the participating operating team members. Further studies focusing on communicational psychology perspective and physiological reaction are recommended.

INTRODUCTION

More complex techniques and equipment are continually added to today's operating room (OR) to assure a more effective, controlled environment for patient health and safety. However, these modern technologies produce noise in the OR that is now comparable to the noise level of a major highway with high traffic density.[1] Persistent, high levels of noise (sound pollution) are known to lead to health problems[2–5] and can affect outcome of surgical procedures[1 6 7] and even OR failures.[8] The volume level and the frequency of noise (sound quality) have negative effects on concentration.[9–12] Higher volumes of noise correlate directly with higher levels of surgical errors, putting patients at risk.[13] The more complex the operation procedures are, the more severe the negative effects of noise become.[14]

The ill effects of long-sustaining sound pollution are well researched in industrial and occupational medicine,[15 16] and work environment noises are restricted by national laws and regulations for occupational safety and health.[17] Unfortunately, there are no specific noise level restrictions for the OR. And although the noise pollution problem in OR is inarguable, very little has been invested to find and develop solutions. Engelmann *et al* showed a significant positive effect with lower rate of OR surgical complications by implementing consequent noise hygiene in the OR: no phones, a ban on non-essential speaking, reduction of alarm sounds of monitor equipment to the minimum and displacement of loud machines as far as possible.[18] Of course, the use of earplugs can reduce noise, even in the OR, but their use also significantly reduces necessary communication. Therefore, a technical solution of the problem is required. The aims of the present study were (1) the reduction of perceived loudness of ambient noise in the OR, (2) improved communication and selective control of information flow among the operating team, and (3) overshadowing of remaining noise by the use of music.

METHODS

Our initial task in developing a technical solution was to research headsets with headphones for noise reduction and microphones for interactive communication. Among the large number of headphones on the market, two general categories of headphones are offered: (1) on-ear and (2) in-ear headsets. We tested seven high-quality models in OR environments regarding their acoustic properties, noise reduction and insulation, wear comfort and disinfection ability. After choosing headsets with the required specifications, they were tested in the OR by different subjects and then tested again in a studio environment to quantify and measure their noise-related properties (figure 1).

For receipt of speech signals and acoustic alarms issued by several devices in the OR, different types of microphones were tested. Microphones with different polarities were used to measure captured noise of various OR equipped with different types of machines and monitors. The effectiveness of noise gates was also tested at different noise levels. The noise gates work in the signal direction of the microphone of a team member speaking, allowing only signals above a predefined threshold to proceed.

For control of information flow within the OR, an internal routing system with multiple designs was tested for creating a communication matrix. Available auditory information and monitoring signals were forwarded to team members. Different connections were determined for each type of operation. Filtered audio signals were available through individual audio channels to team members. Monitor and technical device alarms were categorised and included in the communication matrix. In a team review, each acoustic alarm was rated for its significance and for whom it is significant.

For overshadowing the remaining noise, each team member may listen to individual music at their individually specified volume level. As soon as a member of the operating team speaks, the individual background music volume is lowered to the lowest perceptible volume possible (so-called ducking process).

The first principle of limiting and selecting acoustical information is to not disturb the attention of the team members. This can be achieved by filtering out

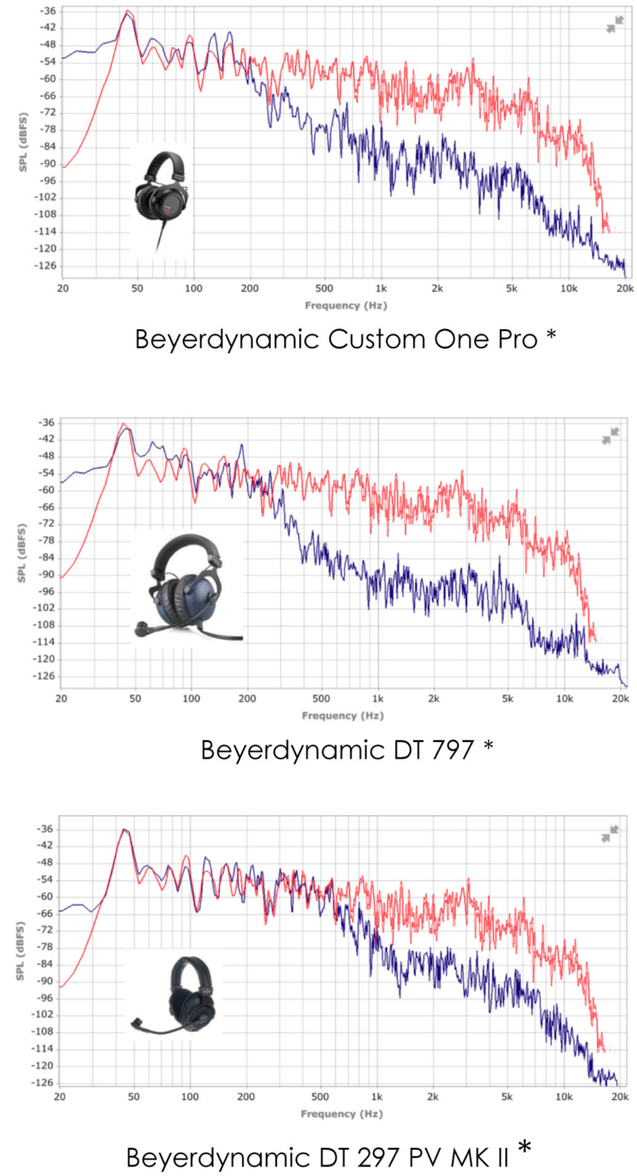


Figure 1 Spectrum analysis (fast Fourier transformations from 20 Hz to 20 kHz) for passive noise reduction inside on-ear headphones without active noise cancelling feature. Blue line: noise reduction, red line: 75 dB pink noise. Reduction of 10 dB means perceived noise is reduced by half. *Headphone without active noise cancelling filter. dBFS, decibels relative to full scale; SPL, sound pressure level.

sounds not belonging to current tasks (eg, non-relevant conversations, patient monitor alarms, patient monitoring beep tones, telephone). Using our own OR background as medical professionals, we structured the communication and information flows by splitting the surgical team into acoustical subgroups. In a cardiac surgery team, for example, we built three subgroups: team 1 is those members positioned directly at the surgical table (primary surgeon, assisting surgeon(s), scrub nurse, perfusionist); team 2 is the scrub nurse and the circulator nurse; and team 3 is the anaesthesiology team. These three teams are audibly interconnected per their need-to-hear/to-be-heard

Friedrich MG, *et al*. *BMJ Innov* 2017;**0**:1–10. doi:10.1136/bmjinnov-2016-000188

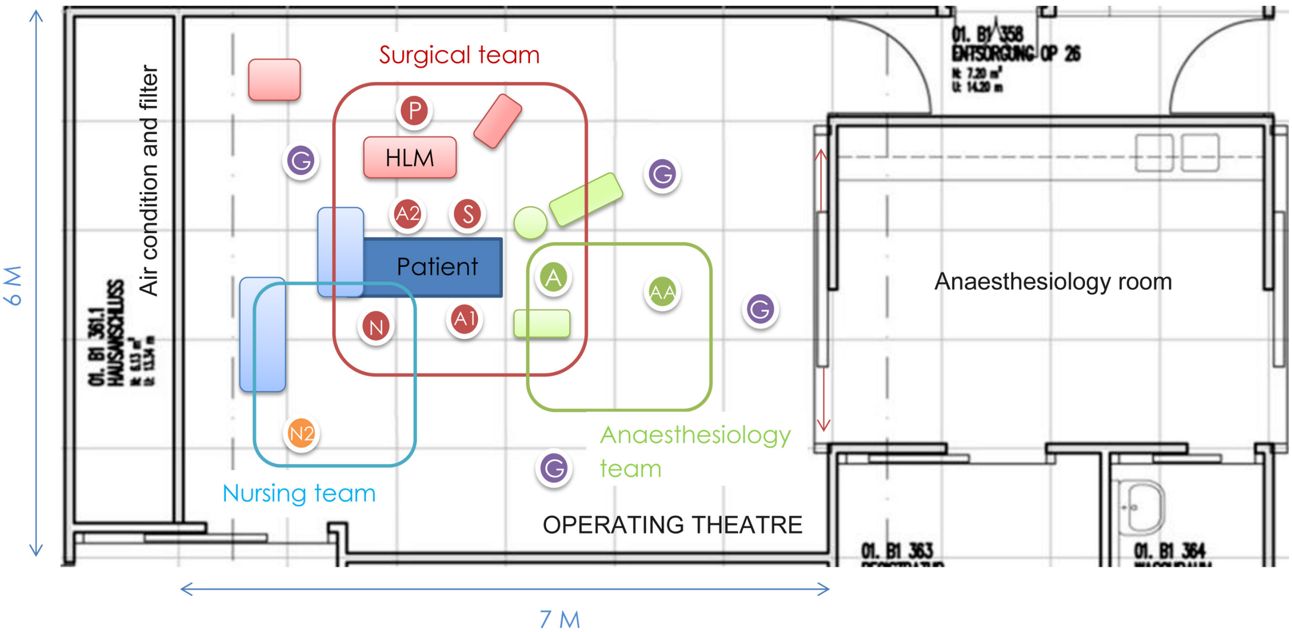


Figure 2 Typical subgroup configuration. There is no need for a special operating room environment—but there is a virtual team composition or communication structure within the SOTOS (Silent Operating Theatre Optimisation System) matrix. Surgical team: S, primary surgeon; A1, first assisting surgeon; A2, second assisting surgeon; P, perfusionist. Nursing team: N, scrub nurse; N2, circulating nurse. Anaesthesiology team: A, anaesthesiologist; AA, anaesthesiologist assistant. Guests (G) are persons not actively involved in the process. HLM, heart lung machine.

requirements (figure 2). The primary surgeon, as team leader, is heard by all team members and all subgroups, but he/she does not hear every other team member unless he/she wants to. The scrub nurse can communicate with the circulating nurse; the anaesthesiologist can speak with the anaesthesiology team or with the perfusionist, and so on.

Development of overshadowing OR residual noise level with individually chosen music resulted in several functional parameters. Music was played in the background on each individual's headset, its volume automatically controlled and modulated by the presence or absence of speech. As soon as one of the team members speaks, generated audio signals result in a suppressed volume of music to a barely audible level (a decrease of 45–60 dB in 0.6 s). Upon an interval of silence longer than 1 s, the music automatically resumes its previous volume. A too abrupt increase or decrease in music volume would lead to unwanted sound level fluctuations or a so-called pump effect. This manipulation of music volume levels prevents loss of information. The music tracks are played in high-quality audio and different styles of music are available (eg, calm piano music, classical music, smooth jazz, pop or live radio stream). The different music styles (audio mixes) are preoperatively agreed upon during team briefing. We found changes of audio mixes throughout the procedure are also possible. Two separate ducking circuits are installed and two separate stereo music sources are controlled by a side chain compressor. Additional overshadowing through the music suppressed the ambient noises to an undetectable level.

The first version of the system assisted 21 operations in cardiac surgery. It was investigated whether the technology is proven and how it was accepted by the team. Immediately after the operation, the team members were asked about their basic acceptance of the communication system and their perception of the wearing comfort (possible grades were: very good/good/fair/poor).

RESULTS

All headsets used in our testing are wire connected. The noise isolating design of the on-ear headphones, which cover the entire auricle of the ear, applied a passive noise reduction level of up to 17 dB (table 1). This decrease means 70% decrease in perceived sound volume. With the use of active noise reduction, its effective noise reduction level was as high as 33 dB, which means 90% decrease in perceived sound volume

Table 1 Passive and active noise reduction effects dB(A) inside of on-ear headsets from 75 dB pink noise outside (for frequency response see figures 1 and 3). Reduction of 10 dB(A) means reduction of perceived noise to the half level

	Noise reduction (dB(A))	
Model	**Passive**	**Active**
DT-297-PV	8	–
DT-797-PV	17	–
Custom One Pro	16	–
HMEC 26-2	14	21
Quiet Comfort 15	17	33

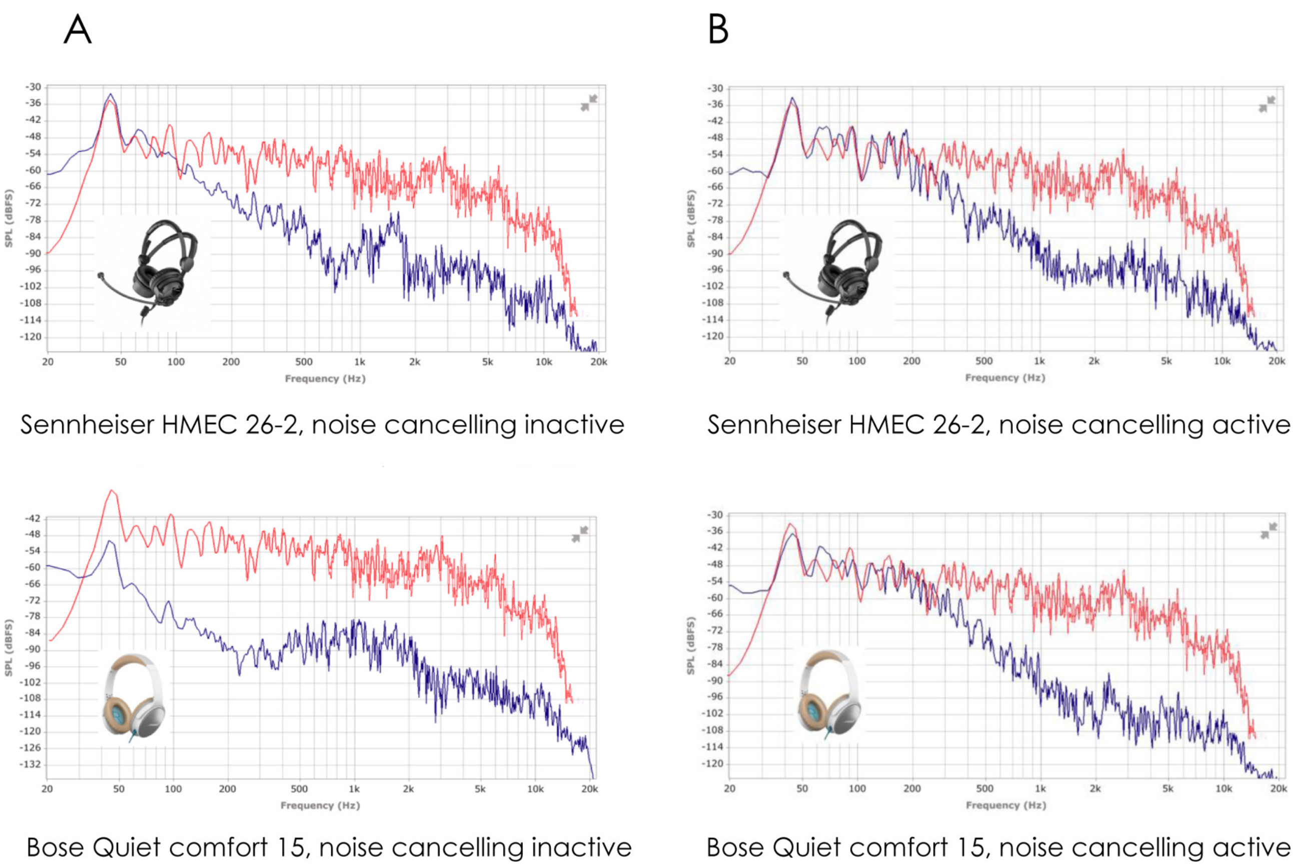


Figure 3 Spectrum analysis (fast Fourier transformations from 20 Hz to 20 kHz) for passive (A) and active (B) noise reduction inside on-ear headphones. Blue line: noise reduction, red line: 75 dB pink noise. Reduction of 10 dB means perceived noise is reduced by half. dBFS, decibels relative to full scale; SPL, sound pressure level.

(table 1). The level reductions do not show a linear reduction to the entire frequency range. Through passive noise reduction, we achieved better reductions in the higher frequencies (figure 1), active noise reduction performed better in low to mid-frequencies (figure 3).

The application of this equipment plus amplitude reduction through frequency-related phase shifting leads to a signal cancellation phenomenon. However, we found that the digital mechanism was not applicable for blocking the entire frequency spectrum due to technical limitations resulting from irregularities of frequencies and unpredictable multiform ambient noise. The headset noise cancelling described above is at its greatest at 50 Hz to <1 kHz, and begins to lose its effect at higher frequencies of about 3 kHz.[19] The majority of speech and verbal information falls into the 2 kHz frequency range.

The tested dynamic spherical type microphones showed a massive interference with background signals. We found an electret condenser microphone with singular direction of signal capturing (cardioid polar pattern) to be optimal for the OR environment (figure 4). These microphones achieved a very good reduction of non-relevant noise interference up to 25 dB. This effect showed an additional improvement by differentiated filtering, which meant using a low-cut filter (128 Hz >20 dB) and suppressing the frequency spectrum off the high-pitched suction device noises (6–12 kHz, reduction 15 dB) and filtering out alarm sounds, which were not muted in the OR (notch filter exactly to the pure tone of the alarm, eg, 840 Hz, reduction 15 dB).

Monitor alarms and device alarms were captured via a separate microphone (Shure Beta 98 H/C, 11–52 V phantom power, polar pattern: cardioid with electret condenser capsule, 20 Hz–20 kHz, Shure Distribution GmbH, Eppingen, Germany).

Using noise gates, signals would undergo a much better and more controlled signal capture criterion. A noise gate must be individually set and configured in relation to the OR ambient noises as well as the sound volume and speech patterns of the team members. The microphones were installed directly in front of the mouth of the speakers in order to access the maximum potential of the microphones' acoustical and noise filtering abilities.

As an additional feature, each audio channel has an end limiter that restricts the sound inflow to a preset maximum level. This protects the team members from uncontrolled spikes in sound levels and volume.

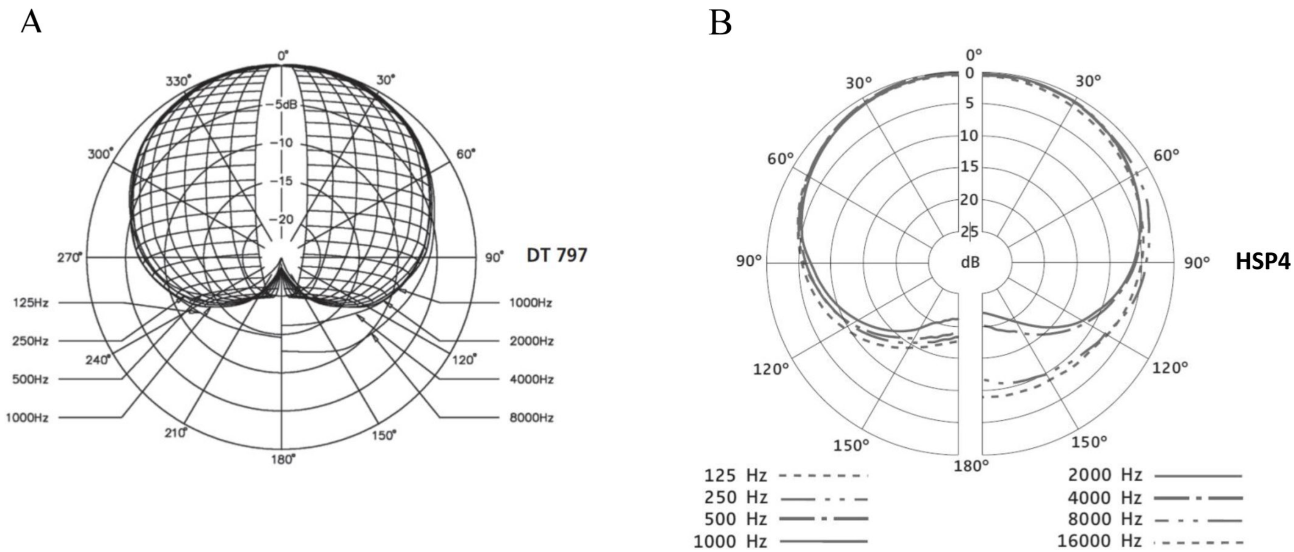


Figure 4 (A) Preferred recording direction of microphone DT 797. Transducer type: condenser (back electret); frequency response: 40–20 000 Hz; polar pattern: cardioid (with permission). (B) Preferred recording direction of microphone HSP4. Transducer type: prepolarised condenser microphone; frequency response: 40–20 000 Hz (with permission).

With the composition of these subsystems (figure 5), we developed a new technical solution to minimise noise exposure for surgical staff: the 'Silent Operating Theatre Optimisation System' (SOTOS).

In the initial engineering of the SOTOS, we built a system that only applied analogue studio technology. The components were wired so that signal entrance pathways, noise gates and signal distributors were connected via four stereo buses. Each team member received an individual signal selection. Only active members were issued a bidirectional headset (microphone and headphone). Persons not directly involved in the procedure were issued hear-only equipment (headphone only, eg, guests).

After the first trials, functions and options required by the system became more evident. Because each of the users in the OR, usually eight persons, was offered an individual audio mix, this raised the complexity of the interconnections to a point where it was no longer possible to implement the communication structure via analogue connections. Thus, we switched to a digitally programmed platform via a digital mixer. We found the X32 (Behringer Music Group, Germany) with its completely open system containing all processes needed for editing signals of 32 channels to be more compatible with our needs. The standard version of the console is small in size and has a small, front control panel. The console is also completely controllable via Wi-Fi. The adaptable matrix allows various mixes for individual users. Nonetheless, programming was very complex and not typical for an audio mixer. The audio hardware programming efforts in this digital version were significantly less troublesome due to digitalisation of interconnected wiring with the X32 control panel. In addition to the digital mixing console and integrated signal pathways, the SOTOS functional parameters require a headset volume controller for the wire-connected headsets. Because of the mobility requirements of the anaesthesiologist and the circulator nurse, they both were issued a wireless bidirectional headset with on-ear speakerphone (16–28 dB noise reduction). A Wi-Fi network was made available in the OR (2.5 GHz, 5 GHz) and to prevent interference, we limited audio transmitted frequencies from 734 to 776 MHz.

In the pilot study, 21 cardiac surgery teams tested the system. None of the team members reported communication problems or technical difficulties. All relevant monitor alarms were heard by the anaesthesiology team. The perfusionist received only relevant alarms from the heart-lung machine. After a short habituation period, a general acceptance of the information flow set-up was reported by all team members. Ninety-five per cent of the surgeons and perfusionists showed very good acceptance. Five per cent found the new system good. Forty-three per cent of the nurses expressed very good acceptance. Fifty-seven per cent found the new system good. Sixty-two per cent of the anaesthetists found the system very good, 29% thought it was good, 9% showed fair acceptance (figure 6).

DISCUSSION

In our cardiac surgery OR, we measured an average background noise level of around 64 dB(A) (54–104 dB(A)). The SOTOS influence on perceived ambient noise during protracted surgeries during the pilot study was clear. Through the design of the speakerphones alone, a noise reduction of approximately 10 dB was achieved. A 10 dB reduction of noise level correlates with a 50% decrease of the original sound volume (perceived loudness). Using digitally generated active noise reduction circuits (active noise cancelling),

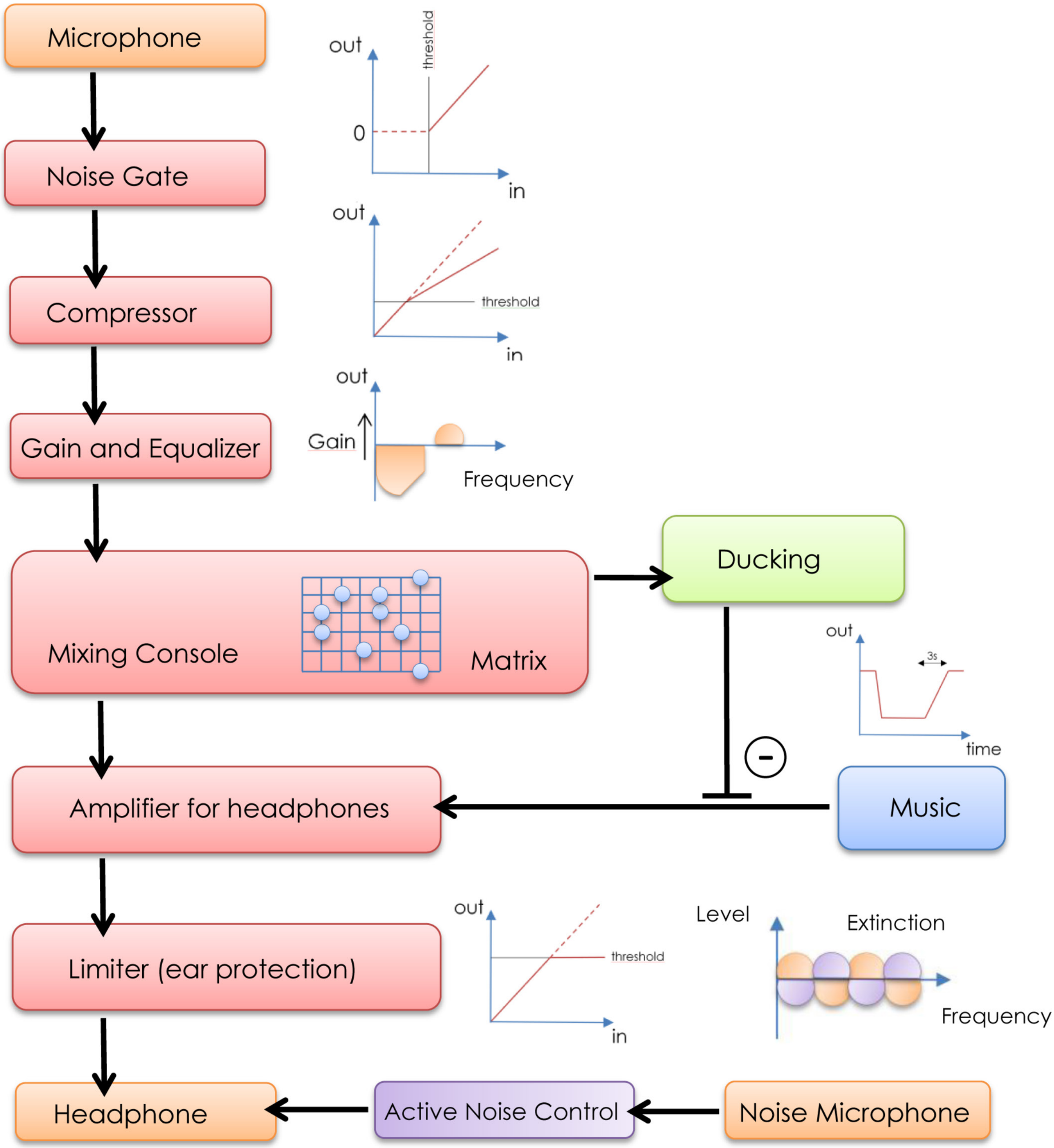


Figure 5 Signal processing and signal pathway of different audio processing components of SOTOS (Silent Operating Theatre Optimisation System). The microphones open only when the team member speaks (noise gate). The compressor reduces very loud speech signals (eg, screaming surgeon) and supports speakers with a low voice. The equaliser adjusts the frequency response for a pleasant listening. Level of music is reduced by the presence of speech (ducking), and for ear protection a limiter is connected directly before each hearing system.

an additional effect of about 30 dB was achieved, which corresponds to a 75% reduction of the noise volume. In total, the applied audio systems of our study achieved a noise reduction of up to 33 dB. In our pilot study in cardiac surgery OR, we measured an average background noise level of around 64 dB. We found sound quality of interteam communication was optimal when using special microphones that suppressed noises in the 180° field in front of the optimal signal capturing area (the mouths of the team members). Well-configured noise gates allowed for more precise filtering of unwanted noise signals in the OR, improving interteam communication sound quality even further. Previous studies state that in order

Friedrich MG, *et al*. *BMJ Innov* 2017;**0**:1–10. doi:10.1136/bmjinnov-2016-000188

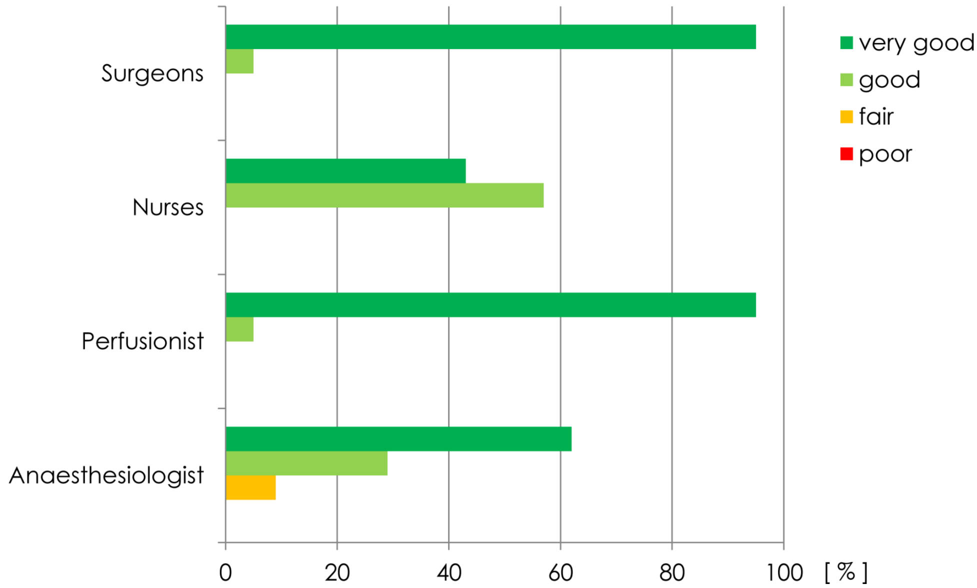


Figure 6 Acceptance grades among subgroups. Data collected by a survey of 21 procedures in cardiac surgery.

to obtain a speech understanding of 90% accuracy, the signal must be presented at 10–15 dB above the noise source.[20–23] Through these described digital interventions of the SOTOS, the achieved difference was up to 25 dB, which improves communication significantly.

In teamwork, most ambient noise can be overcome when team members raise their voice in an effort to be heard. However, multiple team members shouting is known to escalate the situation noise level, making understanding even more difficult.[22 24] Keller *et al* showed that the exchange of information that is directly linked to the task at hand is, in fact, the most harmed.[25] With SOTOS, building flexible selected communication groups that digitally defines need-to-hear/need-to-be-heard team members, unwanted and distracting conversations are blended out (figures 4 and 5).

Clarity of speech rather than sound loudness is essential for efficient communication. Increasing sound level more than 12 dB over the background noise does not affect significant increase in speech quality.[26] Despite optimal volume and frequency transmission, speech quality and definition decreases with increased reverberation times. Ideal reverberation time is below 100 ms (so-called dry acoustic). The greater the distances between communicators, the more prone speech quality is to communication failures. In the OR, speech quality is further compromised by the obligatory surgical masks that mask lip movement.[8] The SOTOS optimised speech transmission by better sound input and output orientation through stereophony and we also found it influenced voice loudness dynamics. The achieved dry acoustic with its close proximity communication meant comfortable communication. This attention paid to speech transmission quality and communication comfort was appreciated by all team members of the pilot study.

The wear comfort of the headset is also essential for acceptance by the OR team. Bidirectional on-ear headsets (hear and speak) are easily mounted on different team members. In-ear systems are better for some persons, for example, if the operating surgeon has to wear magnifying glasses, headlamp or laser glasses. It is also essential that the headset is comfortable and easy to wear, especially in prolonged procedures. In the very first set-up, the anaesthesiologist was not working with a wireless headset. Therefore, the acceptance was worse in these first cases (acceptance fair 9%). Some nurses had problems with their hairstyles under the headsets with headband. This also diminished acceptance (acceptance 'very good': 43%; 'good': 57%) (figure 6). We currently recommend a mobile set-up for each team member with the high-quality headset microphones HSP 4 EW-3 and the in-ear system Quiet Comfort 20 (figure 7). For interference-free wireless transmission, we recommended the Bodypack SK100 G3 and the true diversity receiver EM 100 G3 (figure 7). The costs of this configuration are approximately €1500 per team member.

We observed that the entire team developed a sense of quieter working. For example, unpacking of sterile good was more careful (65 dB/1 m after implementation of the system vs 90–120 dB/1 m prior to implementation). We also noticed that each team member behaved more calmly, not wanting to open one of the noise gates with an unwanted speech signal and preventing the depression of volume of their individually chosen music. Subjectively estimated, these calm verbal behaviours observed in the SOTOS pilot study did not affect procedure-related speech but clearly promoted noise hygiene in the OR.

An additional positive effect of lower sound levels and reduced speech time in the OR environment is lower concentrations of microorganisms in the OR

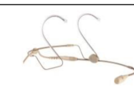
No	model	manufacturer	specification		wear comfort
1	DT 297 PV MK II	Beyerdynamic GmbH & Co. KG, Heilbronn, Germany	Closed headset with dynamic microphone, wired system		poor
2	DT 797	Beyerdynamic GmbH & Co. KG, Heilbronn, Germany	Closed headset with dynamic microphone for use in loud environments, wired system		good
3	HMEC 26-2	Sennheiser electronic GmbH & Co. KG, Wedemark, Germany	Aviation headset, NoiseGard™ wired system		very good
4	Custom One Pro	Beyerdynamic GmbH & Co. KG, Heilbronn, Germany	Closed headphone, 5 Hz - 35kHz wired and wireless with MEI 1000		fair
5	Quiet comfort 15	Bose Cooperation Framingham, United States	On-Ear with active noise cancelling wired and wireless with MEI 1000		good
6	Quiet comfort 20i	Bose Cooperation Framingham, United States	In-Ear with active noise cancelling for wireless with MEI 1000		very good
7	CXC 700	Sennheiser electronic GmbH & Co. KG, Wedemark, Germany	In-Ear with active noise cancelling for wireless with MEI 1000		good
8	HSP 4ew-3-M	Sennheiser electronic GmbH & Co. KG, Wedemark, Germany	Permanently polarized condenser headmic, cardioid pick-up pattern, wireless system		very good
9	SM 35	Shure Distribution GmbH, Eppingen, Germany	Condensor headmic Suitable for loud stages cardioid pick-up pattern		poor
10	MEI 1000 G2	LD Systems Adam Hall GmbH Ansbach, Germany	In-Ear monitoring system wireless transmitter and bodypack, adjustable EQ, limiter function		Ø
11	EM 300 G3 C EU X, SK 100 G3 C	Sennheiser electronic GmbH & Co. KG, Wedemark, Germany	Evolution receiver, 734 - 776 MHz, and bodypack transmitter		Ø

Figure 7 Parts of technical equipment, human interfaces, headsets and transmitter of the Silent Operating Theatre Optimisation System (SOTOS). Perception of wear comfort was asked during the pilot study. Possible answers: very good/good/ fair/poor.

air. Surgical masks typically lose their effectiveness as a barrier to the mouth and nose area after 2 hours, a phenomenon exacerbated especially when speaking in a louder voice.[27 28] SOTOS will therefore likely improve asepsis, especially for prolonged OR procedures.

For the working situation of OR team members, it is important to note that many negative health effects and hazards due to long-term exposure to noise pollution have been reported: high blood pressure, tachycardia, reduced flow in microvessels, organ perfusion reduction and higher cortisol levels. Noise pollution can affect the mechanical skills of the surgeon by tremor, disturbed tactile sensation, worse target movements and less force in muscular coordination.[2 3 29 30]

It is therefore not surprising that adverse outcomes of surgical procedures with higher noise levels have been reported.[1 18 31] There are of course silent operations, but in the OR, levels of noise up to 108 dB have been reported in the preparation phase.[1] Healey *et al* described a median level of 58 dB.[32] Hodge and Thompson found that at times during an OR procedure, noise levels were greater than 80 dB.[1] Furthermore, OR noise levels are expected to rise with new monitoring technologies, surgical devices and increased team size.[19] A direct correlation in massive information loss and increasing OR noise levels has already been observed.[33 34]

An individual adjustment of the stereo field for each participant allowed better spatial orientation and recognition. The digitally generated acoustics resulted in a close proximity feeling of the communication partners. This led to a new way of communication in the OR, with a relaxed tone resulting from the elimination for the need to shout—a feature appreciated by all team members. The SOTOS was perceived as an eliminator of ambient noise and as an innovative way to support task-oriented communication in the OR. It was repeatedly reported, especially from surgeons, that because of the use of the SOTOS, it was much easier to achieve the desired level of high concentration and to sustain it over 6–8 hours duration. In general, team members communicated together in relaxed and smooth speech patterns. We also observed the significant difference the team members registered postoperatively when they removed their headsets and realised the loudness of the unfiltered ambient noise.

The positive effects of music could not be traced to a specific genre of music. Individual listening habits, musical backgrounds, music preferences and the current mental state of the team members undoubtedly impact the effect of music in the OR but are impossible to empirically measure. Research in music psychology has not shown a generalised, consistent pattern of emotional response to music. Our system therefore offers personalised music and enables team members to use their preferred genre. Different media can be used to play and store music. In the SOTOS set-up, we mainly use a high-quality double CD player and a 3 mm stereo jack to serve as an inlet for MP3 players, external play storage units, tablets and smartphones.

In particular, the supportive use of music in a setting comparable to SOTOS has not been studied before. Unlike Nahai, who found that music in the OR disrupted the speech-dependent information exchange,[35] we found that music improved communication, probably because the music applied by the SOTOS was controlled with ducking mechanisms and was present in a greatly noise-reduced OR environment. Our results correlate with those of Faraj *et al*, who reported improvement in cognitive processes, feeling of well-being, improved work efficiency and positive relaxing effects of music in the OR.[36] Our results are also in line with Ullmann *et al*, who accessed 250 surveys, finding 78% of all team members agreed that music in the OR resulted in a calmer work atmosphere and increase in efficiency.[37]

To our knowledge, SOTOS does not require registration as a medical product. It can be integrated into any high-tech environment as a technical aid, provided that standard safety measures are respected. Further studies on SOTOS, including physiological and psychological testing, are ongoing and will be reported.

CONCLUSION

We developed the SOTOS as an effective OR technical noise reduction methodology and communication structure, designed to function with interconnected subgroups using selective signals and specific signal pathways. Thus far, testing has shown that SOTOS can easily implement in the high-tech setting of an operating theatre. These initial positive experiences have encouraged us to further develop the system.

Acknowledgements We thank Nicole Fresen and Sven Boetcher of Sennheiser Electronic GmbH & Co. KG, Wedemark, Germany, for their substantial technical assistance. The authors also thank Margarita Neff-Heinrich, a native English-speaking expat providing professional language editing services in Göttingen, Germany, for editing this report.

Contributors MGF is the corresponding author responsible for the concept/design of SOTOS and the drafting of this report. SR and TT are equal contributing senior authors. MB functioned as the topic expert advisor regarding both the report's content and format. MP, TT and AB all provided support for the report's data analysis/interpretation and statistics.

Competing interests MGF is the inventor of the SOTOS and all included features. The SOTOS is patented and the patent holder is the University Medical Center Göttingen (DE102015205463, PCT/EP2016/056659).

Ethics approval Ethikkommission der Universität Göttingen (No. 12/12/14).

Provenance and peer review Not commissioned; externally peer reviewed.

REFERENCES

1 Hodge B, Thompson JF. Noise pollution in the operating theatre. *Lancet* 1990;335:891–4.
2 Andrén L, Lindstedt G, Björkman M, *et al*. Effect of noise on blood pressure and 'stress' hormones. *Clin Sci* 1982;62:137–41.
3 Babisch W. The noise/stress concept, risk assessment and research needs. *Noise Health* 2002;4:1–11.
4 Babisch W, Fromme H, Beyer A, *et al*. Increased catecholamine levels in urine in subjects exposed to road traffic noise: the role of stress hormones in noise research. *Environ Int* 2001;26:475–81.
5 Burns KN, Sun K, Fobil JN, *et al*. Heart Rate, Stress, and Occupational Noise Exposure among Electronic Waste Recycling Workers. *Int J Environ Res Public Health* 2016;13:140.
6 Kracht JM, Busch-Vishniac IJ, West JE. Noise in the operating rooms of Johns Hopkins Hospital. *J Acoust Soc Am* 2007;121(5 Pt1):2673–80.
7 Love H. Noise exposure in the orthopaedic operating theatre: a significant health hazard. *ANZ J Surg* 2003;73:836–8.
8 Mendel LL, Gardino JA, Atcherson SR. Speech understanding using surgical masks: a problem in health care? *J Am Acad Audiol* 2008;19:686–95.
9 Seidman MD, Standring RT. Noise and quality of life. *Int J Environ Res Public Health* 2010;7:3730–8.
10 Shankar N, Malhotra KL. Noise in the operation theatre: intensity and sources. *Indian J Physiol Pharmacol* 1999;43:263–6.
11 Szalma JL, Hancock PA. Noise effects on human performance: a meta-analytic synthesis. *Psychol Bull* 2011;137:682–707.
12 Szymanska J. Work-related noise hazards in the dental surgery. *Ann Agric Environ Med* 2000;7:67–70.
13 Moorthy K, Munz Y, Dosis A, *et al*. The effect of stress-inducing conditions on the performance of a laparoscopic task. *Surg Endosc* 2003;17:1481–4.
14 Siu KC, Suh IH, Mukherjee M, *et al*. The impact of environmental noise on robot-assisted laparoscopic surgical performance. *Surgery* 2010;147:107–13.
15 Gulian E, Thomas JR. The effects of noise, cognitive set and gender on mental arithmetic performance. *Br J Psychol* 1986;77:503–11.
16 Gulian E, Thomas R. The Effects of Noise, Gender and Cognitive Set. *B Brit Psychol Soc* 1986;39:A42.

17 BAuA AfB-A-G. *Technischen Regeln zur Lärm- und Vibrations-Arbeitsschutzverordnung*: GMBl, 2010:362–431. Nr. 18-20 vom 23. März 2010 S.
18 Engelmann CR, Neis JP, Kirschbaum C, *et al*. A noise-reduction program in a pediatric operation theatre is associated with surgeon's benefits and a reduced rate of complications: a prospective controlled clinical trial. *Ann Surg* 2014;259:1025–33.
19 Sevdalis N, Healey AN, Vincent CA. Distracting communications in the operating theatre. *J Eval Clin Pract* 2007;13:390–4.
20 Moore BC, Glasberg BR. Simulation of the effects of loudness recruitment and threshold elevation on the intelligibility of speech in quiet and in a background of speech. *J Acoust Soc Am* 1993;94:2050–62.
21 Moore BC, Glasberg BR, Vickers DA. Simulation of the effects of loudness recruitment on the intelligibility of speech in noise. *Br J Audiol* 1995;29:131–43.
22 Way TJ, Long A, Weihing J, *et al*. Effect of noise on auditory processing in the operating room. *J Am Coll Surg* 2013;216:933–8.
23 Wiggins-Dohlvik K, Stewart RM, Babbitt RJ, *et al*. Surgeons' performance during critical situations: competence, confidence, and composure. *Am J Surg* 2009;198:817–23.
24 MacLean AR, Dixon E, Ball CG. Effect of noise on auditory processing in the operating room. *J Am Coll Surg* 2013;217:1154.
25 Keller S, Tschan F, Beldi G, *et al*. Noise peaks influence communication in the operating room. An observational study. *Ergonomics* 2016;59:1541–52.
26 Sang J, Hu H, Zheng C, *et al*. Speech quality evaluation of a sparse coding shrinkage noise reduction algorithm with normal hearing and hearing impaired listeners. *Hear Res* 2015;327:175–85.
27 He X, Reponen T, McKay R, *et al*. How does breathing frequency affect the performance of an N95 filtering facepiece respirator and a surgical mask against surrogates of viral particles? *J Occup Environ Hyg* 2014;11:178–85.
28 Ritter MA, Eitzen H, French ML, *et al*. The operating room environment as affected by people and the surgical face mask. *Clin Orthop Relat Res* 1975;111:147–50.
29 Basner M, Babisch W, Davis A, *et al*. Auditory and non-auditory effects of noise on health. *Lancet* 2014;383:1325–32.
30 Nitschke M, Tucker G, Simon DL, *et al*. The link between noise perception and quality of life in South Australia. *Noise Health* 2014;16:137–42.
31 Wong SW, Smith R, Crowe P. Optimizing the operating theatre environment. *ANZ J Surg* 2010;80:917–24.
32 Healey AN, Sevdalis N, Vincent CA. Measuring intra-operative interference from distraction and interruption observed in the operating theatre. *Ergonomics* 2006;49:589–604.
33 Ford DA. Speaking Up to Reduce Noise in the OR. *Aorn J* 2015;102:85–9.
34 Singh SA, Trikha A. Noise levels in the operation theatre environment. *Natl Med J India* 2006;19:112–3.
35 Nahai F. Music in the operating room: "can you hear me now?". *Aesthet Surg J* 2015;35:899–901.
36 Faraj AA, Wright AP, Haneef JH, *et al*. Listen while you work? the attitude of healthcare professionals to music in the operating theatre. *J Perioper Pract* 2014;24:199–204.
37 Ullmann Y, Fodor L, Schwarzberg I, *et al*. The sounds of music in the operating room. *Injury* 2008;39:592–7.

New technical solution to minimise noise exposure for surgical staff: the 'silent operating theatre optimisation system'

Martin G Friedrich, Margarete Boos, Manuela Pagel, Tobias Thormann, Adel Berakdar, Sebastian Russo and Theodor Tirilomis

BMJ Innov published online September 23, 2017