ARCHIVES OF ACOUSTICS
Vol. **41**, No. 4, pp. 683–690 (2016)

*DOI: 10.1515/aoa-2016-0065*

# A Comparison of Handgun Shots, Balloon Bursts, and a Compressor Nozzle Hiss as Sound Sources for Reverberation Time Assessment

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(*received February 16, 2016; accepted July 6, 2016*)

Blank handgun shots, party balloon bursts, and a pneumatic compressor with a small-diameter nozzle were used as sources of sound in the assessments of reverberation time, $T$. The two first sources were of impulse type, while the third one resembled a noise signal source. In this work, 532 values of $T$ were experimentally obtained in four rooms of different volumes and compared. The $T$ values for 1/3 octave frequency bands were found to be independent of the sound source. Reverberation times for the A-frequency-weighting filtered signals were close to one another for the shots and balloon bursts, while those obtained using the compressor nozzle were significantly shorter. The latter effect can be attributed to the relatively high share of high frequency waves in the sound generated by the nozzle. The results show that balloon bursts can be used as handgun shot substitutes in the assessments of reverberation times. While the nozzle noise is rather unsuitable for this purpose, it can be applied in the assessments of $T$ for high frequency waves, up to the ultrasound range. Such acoustic climate information may be useful in designing spaces for high frequency sound-sensitive individuals, e.g. animal shelters.

**Keywords:** reverberation; impulse method; room acoustics; acoustic impact.

## 1. Introduction

Reverberation time ($T$) belongs to the fundamental characteristics of the acoustic climate in closed rooms. Commonly, it is defined as the time necessary for the sound to decay by 60 dB after its source was stopped (ISO 3382-1).

Reverberation plays an important role in architectural acoustics (Beranek, 1993; Chia-Jen Yu, Jian Kang, 2009; Díaz, Pedrero, 2005) due to issues of music and speech perception in concert halls, theatres, cinemas (Boothroyd, 2002; Aretz, Orlowski, 2009; Rudno-Rudziński, Dziechciński, 2006; Yan Zhang, 2005; Opera House Acoustics, 2011), churches (Carvalho, 1995; Kosała, Engel, 2013; Engel, Kosała, 2004), lecture halls and classrooms (Klatte, Hellbrück, 2010; Klatte *et al.*, 2010; Eggenschwiler, 2005; Rasmussen *et al.*, 2012; Yang Daheng, Li Qi, 2012; Nelson *et al.*, 2002). Speech distorted by reverberation is difficult to understand, particularly by persons with hearing loss or intellectual disabilities (Crandell, Smaldino, 2002).

In technical acoustics, $T$ is taken into account when determining the equivalent sound absorption, for instance in the assessments of the sound pressure levels at work stations. Workers fatigue and discomfort could be reduced by making machinery quieter or by installation of acoustic screens in their vicinity. Thus, a knowledge of the noise emitted by machinery and equipment is crucial for proper arrangement of work stations to reduce discomfort. The noise may be assessed from the measured sound pressure levels with local environmental correction, the latter calculated from the surface, volume and the reverberation time of the room where the machinery is installed. $T$ indispensable in the calculations may be obtained either from the values for frequency bands or directly from the A-weighted sound pressure levels (ISO 11204).

Precise determination of $T$ is possible using interrupted methods which employ an application of a random noise signal, e.g. white or pink noise, generated by an omnidirectional loudspeaker. The decay time of the signal is then measured after the loudspeaker is turned off. Alternatively, impulse sources may be applied (ISO 3382-1, ISO 3382-2, Passero, Zannin, 2010; Horvat *et al.*, 2007). Acoustic impulse can be created by a blank handgun shot or a balloon burst (Broch, Jensen, 1966). Other acoustic impulse sources have been suggested, e.g. firecrackers or a wooden clapper (Sumarac-Pavlovic *et al.*, 2008). While it is relatively easy to provide a sufficiently high signal to noise (S/N) ratio using these low-cost sources, their signal energy tends to be unevenly distributed across a wide range of frequencies and, for this reason, they are suitable only for the reverberation time assessment in such rooms as, e.g. industrial spaces, shopping centers, indoor arenas and majority of the classrooms.

In this work, we have compared three types of the sound sources: party balloons filled with air, a handgun with blank cartridges, and an air compressor equipped with a small-diameter nozzle. The first two are impulse sources, while the third one resembles the noise signal source. The aims of this study are: (i) to compare $T$ values obtained with the aid of two impulse sources and (ii) to determine whether a very simple noise machine can aid in the assessment of $T$. No efforts have been made to discuss aspects of building acoustics as, *e.g.* the size and shape of the rooms or absorption and scattering properties of the building materials.

## 2. Experimental

Reverberation time was assessed according to recommendations of the ISO 3382-1 standard. Two measuring sets were used to record and analyze acoustic signals in this work and they are described in Table 1. The sound pressure level, $L$, was recorded in 1/3 octave bands of center frequency from 100 Hz up to 20 kHz and 40 kHz for the measuring sets #1 and #2, respectively. Since the meters complied with IEC 61672-1 standard, the A-frequency-weighting filtered values (sound levels, $L_A$) were recorded directly as well and applied in the assessment of the reverberation time for A-weighting, which is permitted by ISO 11204 standard. To avoid unjustified generalizations, the experiments were carried out in four rectangular rooms of various sizes, see Table 2.

The measuring set #1 utilized four microphones mounted on stands 1.5 m high and arranged symmetrically around the acoustic signal source located ∼0.5 m higher, as shown in Fig. 1. In the experiments with the measuring set #2, the broadband microphone was installed on one of the stands. The distances between microphones complied with ISO 3382-2 standard. A compliant source – microphones arrangement was impos-

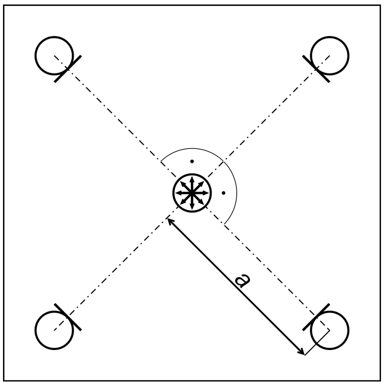

Fig. 1. Experimental setup: four microphones around the acoustic signal source; $a \approx 2$ m except the small room where $a \approx 1$ m. Distances to the room walls are not in the picture scale.

Table 1. Characteristics of the measuring sets used in the experiments.

| Set # | Meter – analyzer | Pre-amplifier | Microphone | Sampling interval (ms) |
|---|---|---|---|---|
| 1 | Four channel noise and vibration analyzer Svantek Svan 958 | Svantek SV 12L (four pcs) | 1/2 inch BSWA Technology SV 22 (four pcs) | 10 |
| 2 | Noise and vibration analyzer Svantek Svan 912 AE | Svantek SV 01 A | 1/4 inch G.R.A.S. 40 BF | 8 |

Table 2. Characteristics of the interiors where the experiments were carried out.

| Room | Dimensions[a] [m] | Volume [m$^3$] | Walls | Ceiling | Floor | Doors, gates and windows | Remarks |
|---|---|---|---|---|---|---|---|
| Small | 1.80 × 1.50 × 2.85 | 7.70 | Panels[b] | Panels[b] | Fitted carpet | One wooden door | Empty room |
| Medium-sized | 4.50 × 3.30 × 2.85 | 42.32 | Panels[b] | Panels[b] | Fitted carpet | One wooden door, one window ca. 1 m$^2$ | Empty room |
| Stockroom | 2.90 × 2.90 × 2.40 | 20.18 | Concrete | Concrete | Concrete | One steel door | Empty room |
| Assembly plant | 108.96 × 15.24 × (from 9.50 to 10.28) | 16500 | Concrete | Ribbed steel roof | Concrete | Several gates and doors, windows in one long wall | Room with machinery and equipment installed |

[a] length × width × height, [b] Calcium silicate board perforated acoustic panels.

sible in the small room because of its size ($V = 7.7$ m$^3$); however, the results for this room are included due to the goal of this study being to compare sound sources rather than to characterize enclosures. The source and microphone locations remained unchanged in each enclosure throughout the series of measurements over several hours in duration. Temperature, pressure and humidity of air were constant as possible given the environmental control capabilities of the location. The A-weighted background noise was approximately constant and equal to 35 dB in the assembly plant and ca. 30 dB in the other rooms.

The propagation of heat caused by gunshots was recorded by a thermographic camera Flir S.C. 660.

## 3. Results

Frequency characteristics of a gunshot, a balloon burst, and those of nozzle hisses are plotted in Fig. 2. The corresponding numerical data are provided in the supplementary materials Table S1. Figure 2 shows that the frequency ranges of the sound waves emitted by the three sources likely extend beyond the measurement range of either of the two apparati used. Three of the four frequency characteristics, marked (a), (b), and (c) in Fig. 2, were recorded in the stockroom and with the same distances between the sound source and the microphone. The $L_A$ values were 133, 126, and 92 dB for the shot, the balloon burst, and the nozzle hiss, respectively. The data also show that the recorded sound pressure levels are dependent on experimental conditions, as is evidenced by two different results obtained for the compressor nozzle hiss, cf. lines (c) and (d) in Fig. 2. Nevertheless, general features of these two signals generated by the same source remained unchanged.

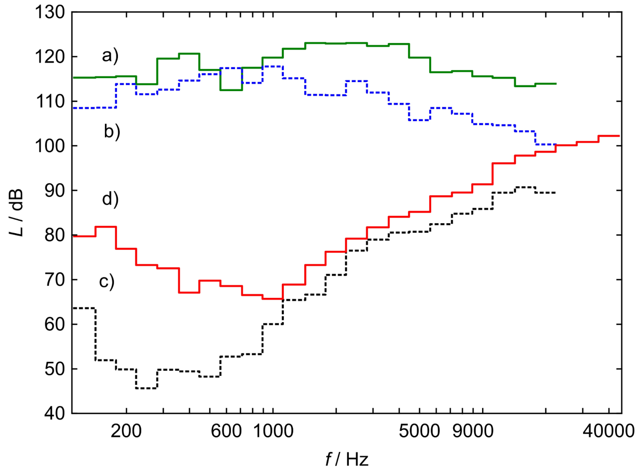

Fig. 2. Frequency characteristics of the sources in 1/3 octave bands: a) a gunshot, b) a balloon burst, c) a compressor nozzle hiss recorded in the stockroom, d) a hiss recorded in the small room using measuring set #2.

The $L$ distributions for the gun and for the balloons are approximately uniform with flat maxima in the bands of center frequencies 1250–4000 Hz and 500–1250 Hz, respectively. Much higher frequency waves predominate in the nozzle hiss. The maximum may lie in the 40 kHz band or even at a higher frequency outside these measurements range. The observation of the measured $L$ values as a function of sound frequency reveals that the nozzle hiss is (i) rich in the acoustic energy in the ultrasound range ($f > 16$ kHz) and, in contrast to the $L$ distributions observed for balloon bursts and gunshots, very likely to be (ii) distributed bimodally, with the second maximum occurring at 125–160 Hz with $L$ values being significantly lower than that at 40 kHz.

The acoustic signals generated by the sources studied in this work prove to be isotropic in the plane parallel to the floor. The mean relative ranges of the $L_A$ values recorded by four microphones around the source did not exceed 2.8% and had rather small standard deviations, as illustrated in Fig. 3. Consequently, all calculated reverberation times are statistically equally weighted from here on.

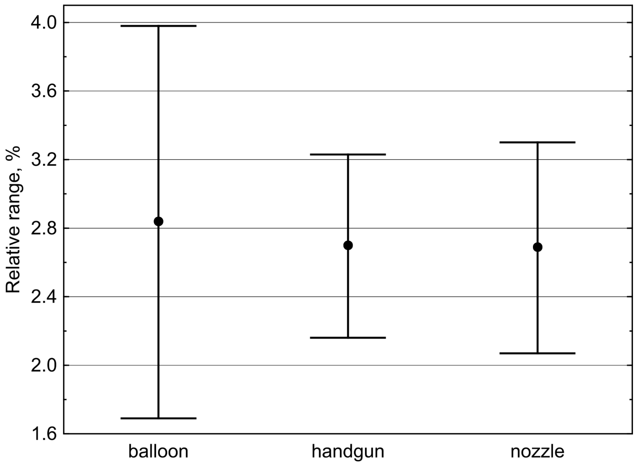

Fig. 3. Relative ranges of the maximum sound levels recorded by four microphones placed around the sound sources; points – mean value of the range, whiskers – (mean value ± standard deviation).

The sound pressure level changes that accompany firing of the handgun, balloon bursts, and switching off the compressor nozzle were recorded. Each one of the sound pressure level records consists of ~1000 data vectors, representing the sound pressure levels in 1/3 octave frequency bands and the A-filtered values. The entire range of sound pressure level changes during one acoustic event was sampled, starting from the background level, followed by a rapid increase as the sound was generated, and the subsequent pressure decrease back to the background level. Examples of the sound level curves are plotted in Fig. 4. In the middle of the decay range, a linear dependence of the level on time is observed.

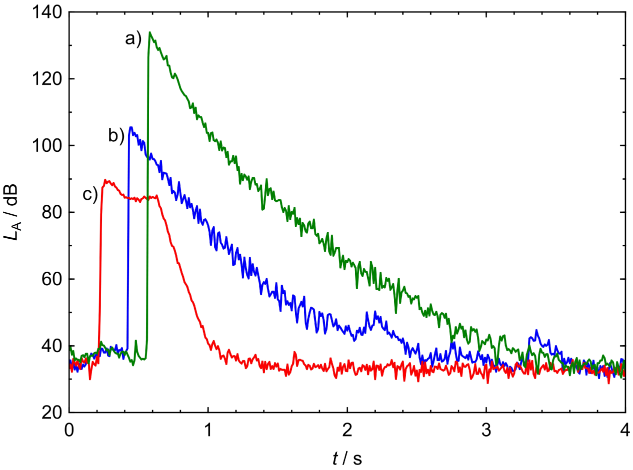

Fig. 4. Sound level *vs.* time curves obtained using three sound sources in the stockroom: a) a gunshot, b) a balloon burst, c) a compressor nozzle hiss.

The data from the linear decay range were used in the calculations of the reverberation time, $T$, according to the formula:

$$L = L_0 - \frac{60\,t}{T}, \tag{1}$$

where $L$ is the sound level (dB) or sound pressure level for 1/3 octave frequency bands, and $t$ is time (s). The rise axis intercept, $L_0$, has no physical meaning, as it depends on the arbitrarily chosen value of the initial time.

The "Advanced linear/nonlinear models" module of Statistica 10 software package (StatSoft, Inc., 2011) was used in the calculations of reverberation times by the least squares fit of Eq. (1) to the experimental values of the sound levels in the range of linear decay. This range was at least 20 dB wide, with 30 dB width being the most common among the measurements. Sample fit is shown in Fig. 5. A total of 184 individual estimates of $T$, with standard errors, were collected and are summarized in the supplementary material Table S2. In similar way, reverberation times in the stockroom were calculated for the 1/3 octave bands. These $T$ values with standard errors are reported in the supplementary material Tables S3–S6.

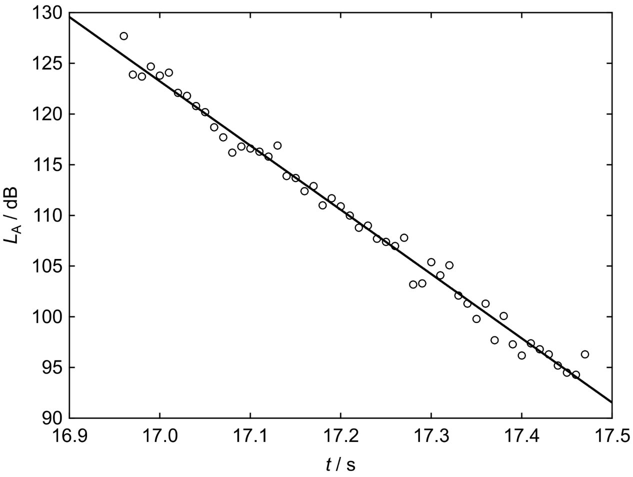

Fig. 5. Linear decrease of the sound level after firing the handgun; points – experimental values; line – simple linear regression (Eq. (1)).

Distributions of the reverberation times for the three sound sources are reported in Figs. S1–S3 attached as supplementary materials. Normal distribution fit usually failed, which was confirmed by the results of Shapiro-Wilk tests (StatSoft, Inc., 2011). Consequently, medians rather than arithmetic means were used as the expected values of the reverberation time. Rather small standard errors in $T$ obtained from the decay curves mean that the uncertainty in reverberation times is driven by the large range of all results for the sound source in a given room. Differences between the reverberation times assessed using the three sound sources and the scatter of the results are illustrated by the $T$ quartiles plotted in Fig. 6. $T$ in the large assembly plant was 3.04 s (with the range of 0.32 s) and 3.01 s (range 0.34 s) for gunshots and balloon bursts, respectively.

Since blanks of only one type were used (as supplied by one manufacturer from one production batch) it is conceivable that the repeatability of the reverberation times obtained using different blanks would be somewhat poorer. Likewise, the quality of the blanks (and balloons) used in these experiments as the sound sources was not assessed.

A comparison of the reverberation times for 1/3 octave frequency bands obtained for the stockroom using all three sound sources is reported in Fig. 7. Contrary to the $T$ values for the sound levels (see Fig. 6c), the agreement of the results obtained for the three sound sources is very good for the frequencies above 400 Hz. At low frequencies, however, the experimental sound pressure levels decay with distinct scatter or fluctuations around the interpolated straight line, most likely due to at least two closely spaced modes of vibration excited by the sound source in the room (Beranek, 1993).

Taking into account the uneven distribution of energy in the frequency bands, a method according to the ISO 3382-1 standard was applied, in which the one-value reverberation time was approximated by the average of those for 1/3 octave frequency bands with center frequencies from 400 to 1250 Hz. This approach yielded fairly consistent values of $T$ for the stockroom when using the three sound sources: 0.96 s with the range of 0.06 s for balloons, 0.97 s (range 0.06 s) for handgun shots and 0.92 s (range 0.11 s) for the compressor nozzle. The averages for the bands from 100 to 5000 Hz (i.e. for the narrowest frequency range in the precise and engineering methods according to ISO-3382-1) agreed slightly worse, due to considerable uncertainties associated with the data for frequencies be-

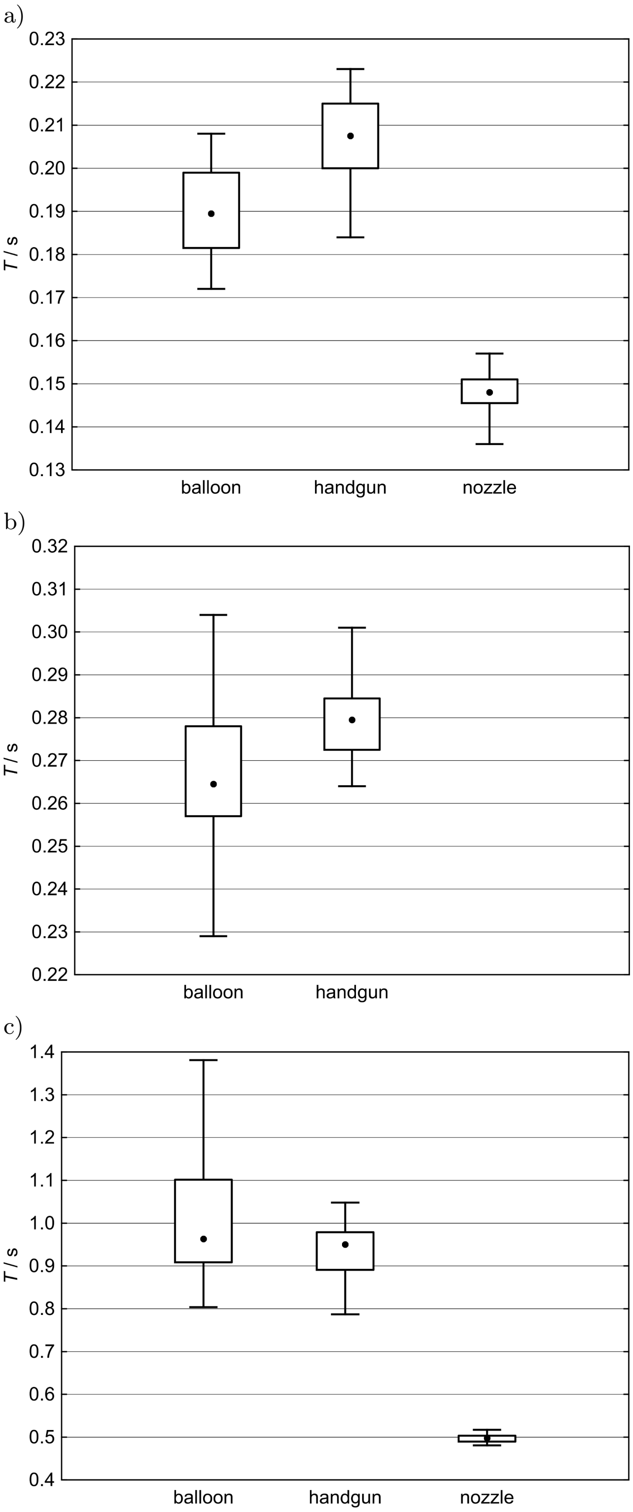

Fig. 6. Quartiles of the reverberation times assessed with the three compared sound sources in three rooms: a) small room, b) medium-sized room, c) stockroom. Points – medians, boxes – 25% to 75% range, whiskers – full range.

low 400 Hz. They were: 1.18 s with the range of 0.07 s for balloons, 1.13 s (range 0.16 s) for handgun shots and 1.24 s (range 0.29 s) for the compressor nozzle.

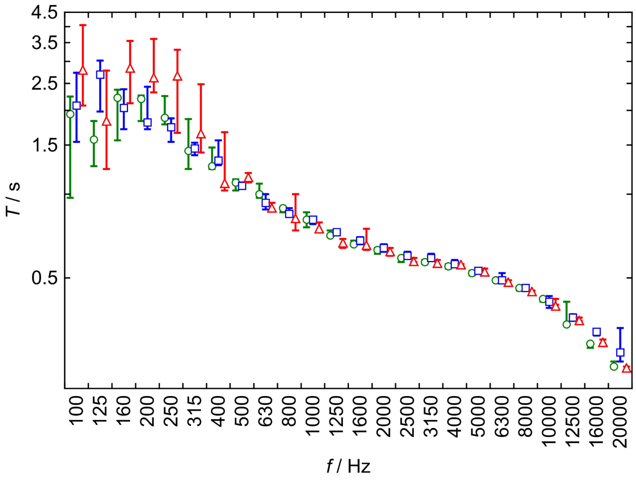

Fig. 7. Reverberation times in the stockroom for 1/3 octave frequency bands: balloon bursts (◇), handgun shots (◯), nozzle hiss (△). Each point represents a median of four results, whiskers encompass their ranges.

## 4. Discussion

The major signatures of the sound level *vs.* time curves obtained with the aid of balloon bursts and handgun shots are similar to one another, with the maxima for the balloon bursts being lower than those for the gunshots (Fig. 4). The slopes in the linear decay range are approximately the same, which leads to similar values of $T$. However, although the sound level change due to the gunshot is isotropic in the plane parallel to the floor (Fig. 3), the handgun does not appear to be an omnidirectional sound source, if one assumes that the sound propagation mimics that of the temperature distribution in the vicinity of the gun muzzle just after a shot (Fig. 8). This notion is further sup-

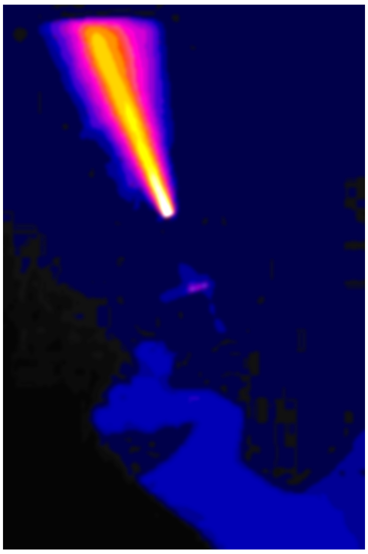

Fig. 8. Thermal image of temperature distribution after discharging of the handgun used in this study.

ported by the previously reported directivity of sound emitted by 23–155 mm caliber weapons (Pääkkönen *et al.*, 2001). Accordingly, sound level may be different in front, behind, or beside the firearm at the same distance from the gun muzzle. A balloon burst is probably a nearly omnidirectional source of sound. Different directivities of handgun shots and balloon bursts are particularly important for the results for small rooms. In contrast, as the room volume increases, the difference between reverberation times assessed using the gunshots and balloon bursts vanishes (Fig. 6). For the large assembly plant, medians and ranges of $T$ are virtually identical for these two sound sources.

As seen in Fig. 6, the reverberation times obtained with the gunshots and the balloon bursts are close one to another. Differences between the two medians are smaller than 10% and approximately equal to the interquartile range for each individual room. On the other hand, the values of $T$ measured upon the use of the compressor nozzle were found to be significantly shorter. This may be the result of the relatively high share of the high-frequency waves in the nozzle hiss (Fig. 2), as expected due to the reverberation being a frequency-dependent phenomenon (Broch, Jensen, 1966). Reverberation times measured in this study were shorter for waves of higher frequencies (Fig. 7). Although fairly common, this is *not* a general rule. Departures may result from such reasons as different characteristics of building materials or the shape of the interior (Beranek, 1993; Iannace, Trematerra, 2014; Kosała, Engel, 2013). It is worthwhile to notice that the approximate equity of the $T$ assessed when using the three sound sources was observed for the 1/3 octave frequency bands, as seen in Figs. 7 and 9. The latter figure shows distributions of the results for the stockroom, obtained from 20 balloon bursts, 24 handgun shots and 20 nozzle hisses for the 1/3 octave band with 2 kHz center frequency.

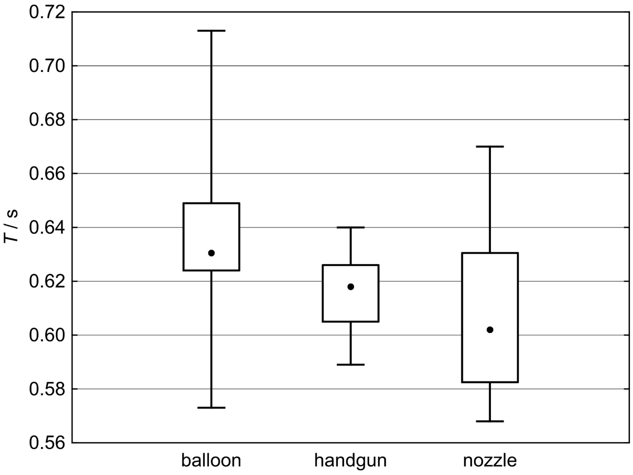

Fig. 9. Quartiles of the reverberation times for the 1/3 octave band with 2 kHz center frequency, determined in the stockroom. Sound generated by the three compared sources: points – medians, boxes – 25% to 75% range, whiskers – full range.

As seen in Fig. 4, the acoustic responses to the sound emitted by the compressor nozzle differed significantly from the responses to the signals of the two other sources. Notably, the linear decrease of $L_A$ with time was steeper and the maximum sound levels attainable were ∼20–40 dB below the maxima for the balloon bursts and gunshots. The compressor nozzle generated sound waves of relatively high frequencies and rather low sound pressure levels in the hearing range. Due to the rather uneven distribution of energy, with a minimum in 1/3 octave bands of center frequency between 200 and 1000 Hz (Fig. 2), the nozzle hiss was shown to be unsuitable for the assessment of the reverberation time for the A-weighted sound levels. Instead, it may be useful in reverberation studies in the ultrasound range. While humans are not sensitive to very high-pitch sounds, cats and dogs can hear sounds up to 50 and 80 kHz, respectively. Generally, smaller mammals have better high-frequency hearing than the larger ones do (Heffner, Heffner, 2007). For that reason, ultrasonic devices have been routinely employed to deter nuisance animals. One could propose that the knowledge of the acoustic climate, including the presence of sounds with high frequencies, would be important in designing spaces for animals, such as animal shelters. To the best of our knowledge, reverberation times of ultrasounds have never been considered. Indeed, the fact that high frequency waves are highly directional and better attenuated by air than the low-frequency ones, may have discouraged researchers from pursuing this angle in the past.

One-value reverberation times approximated by the averages of the times for frequency bands are independent of the sound source within the measurement uncertainty range. Even the compressor hiss results do not significantly deviate from those obtained with handgun shots and balloon bursts. Contribution of considerable uncertainties of the low-pitch times (for the bands with center frequencies below 400 Hz) in the combined uncertainty of $T$ is compensated by rather low uncertainties of those for higher frequencies. This makes the averaged $T$ results more reliable than those based on the sound level decay curves.

## 5. Conclusions

We have employed three different sound sources to study reverberation times in various size rooms, namely handgun shots, balloon bursts, and the compressor nozzle hiss. Party balloons constitute a reliable sound source for the reverberation time assessment, especially in small or low-ceiling rooms, and in rooms in which the use of firearms is prohibited due to safety and other reasons. They do, however, generate lower maximum sound levels compared to the gunshots as well as yield reverberation times with slightly decreased repeatability.

The pneumatic nozzle generates sound with unflat spectrum, with the sound pressure levels maxima in the ultrasound range, which makes it suitable for an assessment of the high-frequency sound reverberation times. The reverberation times assessed for the A-weighted sound obtained using a nozzle have been shown to be significantly shorter than those generated with gunshots and balloon bursts. However, another nozzle capable of generating sound with nearly uniform distribution of energy in all the 1/3 octave bands could be a suitable solution for the A-sound reverberation measurements.

The reverberation times obtained experimentally for waves in 1/3 octave bands proved to be independent of the sound source used. Consequently, one-value reverberation times, assessed as averages of the results for several frequency bands, were found to be both consistent and reliable. The uncertainty of $T$ for the pneumatic nozzle as the sound source was slightly worse than those for the two other sources.

## Associated content

Supporting Information

Frequency characteristics of the sound sources, A-filtered and 1/3 octave bands reverberation times, distributions of the reverberation times. The Supporting Information is available free of charge on the *Archives of Acoustics* website.

## Acknowledgments

The study was funded by the IOMEH core funding for statutory R&D activities in 2014 (ZSFF-PiE – 3). Financial support from the Polish National Centre for Research and Development (NCBiR) grant INNOTECH-K2/IN2/40/182367/NCBR/13 is acknowledged.

The authors gratefully thank inż. Wacław Wittchen from the Instytut Metalurgii Żelaza in Gliwice, Poland, for providing thermal images. They are sincerely indebted to Dr. Elizabeth Cook for reading the manuscript and making corrections.

## References

1. Aretz M., Orlowski R. (2009), *Sound strength and reverberation time in small concert halls*, Appl. Acoust., **70**, 1099–1110.
2. Beranek L.L. (1993), *Acoustics*, Acoustical Society of America, New York.
3. Boothroyd A. (2002), *Room acoustics and speech perception*, San Diego State University, Retrieved February 1st, 2016 from http://www-rohan.sdsu.edu/~aboothro/files/Papers_on_RoomAcoustics/Roomacousticsandspeechperception.pdf
4. Broch J.T., Jensen V.N. (1966), *On the Measurement of Reverberation*, Bruel and Kjaer Technical Review No. 4-1966.
5. Carvalho A.P.O. (1995), *The use of the Sabine and Eyring reverberation time equations to churches*, 129th meeting of the Acoustical Society of America, Washington DC, Retrieved February 1st, 2016 from http://paginas.fe.up.pt/~carvalho/asa129.pdf; abstract: Carvalho A.P.O. (1995), J. Acoust. Soc. Am., **97**, 3319.
6. Chia-Jen Yu, Jian Kang (2009), *Environmental impact of acoustic materials in residential Buildings*, Building and Environment, **44**, 2166–2175.
7. Crandell C.C., Smaldino J.J. (2002), *Classroom Acoustics for Children With Normal Hearing and With Hearing Impairment*, Lang. Speech Hear. Serv. Sch., **31**, 362–370.
8. Díaz C., Pedrero A. (2005), *The reverberation time of furnished rooms in dwellings*, Appl. Acoust., **66**, 945–956.
9. Eggenschwiler K. (2005), *Lecture Halls – Room Acoustics and Sound Reinforcement*, 4th European Congress on Acoustics (Forum Acusticum 2005), Budapest, Hungary, 2059–2064.
10. Engel Z., Kosała K. (2004), *Reverberation indices in acoustic assessments of sacral structures*, Arch. Acoust., **29**, 1, 45–59.
11. Heffner H.E., Heffner R.S. (2007), *Hearing Ranges of Laboratory Animals*, J. Am. Assoc. Lab. Anim. Sci., **46**, 11–13.
12. Horvat M., Jambrosic K., Domitrovic H. (2007), *Methods of measuring the reverberation time*, 3rd Congress of the Alps Adria Acoustics Association, Graz – Austria.
13. Iannace G., Trematerra A. (2014), *The acoustics of the caves*, Appl. Acoust., **86**, 42–46.
14. IEC 61672-1 (2013) Electroacoustics. Sound level meters. Part 1: Specifications.
15. ISO 11204:2010 E, *Acoustics – Noise emitted by machinery and equipment – Measurement of emission sound pressure levels at work station and at other specified positions – Method requiring environmental corrections.*
16. ISO 3382-1:2009. *Acoustics – Measurement of room acoustic parameters – Part 1: Performance spaces.*
17. ISO 3382-2:2010, *Acoustics – Measurement of room acoustic parameters – Part 2: Reverberation time in ordinary rooms.*
18. Klatte M., Hellbrück J. (2010), *Effects of classroom acoustics on performance and wellbeing in elementary school children: A field study*, Proceedings of the 39th International Congress on Noise Control Engineering, Internoise 2010, Lisbon, Retrieved February 1st, 2016 from https://www.sowi.uni-kl.de/psychologie-ii/publications/of-maria-klatte/#c1869.

19. Klatte M., Hellbrück J., Seidel J., Leistner P. (2010), *Effects of classroom acoustics on performance and wellbeing in elementary school children: A field study*, Environment and Behavior, **42**, 659–692.

20. Kosała K., Engel Z.W. (2013), *Assessing the acoustic properties of Roman Catholic churches: A new approach*, Appl. Acoust., **74**, 1144–1152.

21. Nelson P.B., Soli S.D., Seltz A. (2002), *Classroom Acoustics II. Acoustical Barriers to Learning*, Technical Committee on Speech Communication of the Acoustical Society of America, Melville NY, Retrieved February 1st, 2016 from http://asa.aip.org/classroom/bookletII.pdf

22. Opera House Acoustics (2011), Proceedings of the 17th International Congress on Acoustics, Rome 2011, Retrieved February 1st, 2016 from http://www.icacommission.org/Proceedings/ICA2001 Rome/5_09.pdf

23. Pääkkönen R., Parri A., Tiili J. (2001), *Low-Frequency Noise Emission of Finnish Large-calibre Weapons*, J. Low Freq. Noise V.A., **20**, 85–92.

24. Passero C.R.M., Zannin P.H.T. (2010), *Statistical comparison of reverberation times measured by the integrated impulse response and interrupted noise methods, computationally simulated with ODEON software, and calculated by Sabine, Eyring and Arau-Puchades' formulas*, Appl. Acoust., **71**, 1204–1210.

25. Rasmussen B., Brunskog J., Hoffmeyer D. (2012), *Reverberation time in class rooms – Comparison of regulations and classification criteria in the Nordic countries*, Proceedings of Joint Baltic-Nordic Acoustics Meeting, Odense, Denmark, Retrieved February 1st, 2016 from https://www.researchgate.net/publication/233729033_Reverberation_time_in_class_rooms_-_Comparison_of_regulations_and_classification_criteria_in_the_Nordic_countries

26. Rudno-Rudziński K., Dziechciński P. (2006), *Reverberation time of Wrocław Opera house after restoration*, Arch. Acoust., **31**, 4S, 247–252.

27. StatSoft, Inc. (2011), STATISTICA (data analysis software system), version 10. www.statsoft.com

28. Sumarac-Pavlovic D., Mijic M., Kurtovic H. (2008), *A simple impulse sound source for measurements in room acoustics*, Appl. Acoust., **69**, 378–383.

29. Yang Daheng, Li Qi (2012), *Research of Computer Simulation of Reverberation Time in Classroom*, Physics Procedia, **33**, 1677–1682.

30. Yan Zhang (2005), *A Method to Predict Reverberation Time in Concert Hall Preliminary Design Stage*, PhD Dissertation, Georgia Institute of Technology, Retrieved February 1st, 2016 from https://smartech.gatech.edu/bitstream/handle/1853/7452/yan_zhang_200512_phd.pdf