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Research article

Investigating the effects of geometry and material on acoustic characteristics of hospital rooms

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Abstract

The purpose of this study is to find solutions to improve the acoustic characteristics of therapeutic spaces in the design and construction phases. In many architectural designs, the importance of acoustics is not considered, although the acoustic performance of buildings is of importance in many cases. Hospitals are one of such cases. This study is focused on the effect of the geometry and material of the internal walls of the patient's hospital room on its acoustic performance through computer acoustic simulations. Acoustic simulations have been implemented in Odeon software. The acoustic calculations in this software are geometric and the most important acoustic parameters of the patient's room have been investigated. Reverberation time is one of the key parameters. A set of dimensions and common materials for a hospital room were considered as input for acoustic simulation. The results of this research specifically suggest the optimal dimensions and materials of a three-bed patient room. Based on the simulations, a three-bed room with dimensions 5.3 x 1.7 square meters and vinyl wall material leads to the optimal amount reverberation time. Although the use of porous acoustic material in the walls can significantly improve the acoustic characteristics of the room, but due to the health considerations of infectious environments, the use of such materials is not allowed. In some cases, conflicts arise between the methods of improving these multiple parameters. In this study, the reverberation time has the highest priority over other parameters.

Keywords: Medical space architecture, Acoustics, Noise reduction, Closed space, Building materials.

1- Introduction

Today, medical spaces are considered as healing spaces [1]. A healing space must have positive effects on those using that space. Architecture is one of the key factors for achieving such a space. Proper architectural design can lead to noise reduction which has adverse effects of patients' health [2]. Noise pollution is one of the major stressor factors for patients and staff members in hospitals. The findings of various studies show that in medical centers, reducing noise pollution can improve patients' satisfaction, improve the quality of their sleep and reduce their blood pressure [3-5]. Furthermore, staff members also have better performance and efficiency at places with low noise pollution [6, 7]. Today, the existence of excessive noise in medical environments is unacceptable and requirements are suggested to improve the acoustic conditions [8-10].

Unfortunately, the auditory sense is neglected by many architectural designers [11]. It must be remembered that hearing is the last sense to stop working during sleep and is also the first to be active when waking up. However, often visual representations are the only significant factor considered during architectural design.

The process of architectural design is often based on the desired applications and needs. In some cases, these needs are available as mandatory or voluntary standards and regulations. It is evident that architectural design must be appropriate to the application and purpose of the space. In other words, architectural design must provide suitable comfort and conditions for the intended use of the space. Therefore, architectural design of a building must consider all aspects and factors affecting the comfort of the users. Acoustic considerations are some of the most important factors which must be considered. The acoustic characteristics of various buildings such as cinema and concert halls, medical centers, classrooms, libraries, hotels, malls, office buildings and residential buildings are different based on the specific applications and must be considered during the design phase [12]. Despite lack of direct attention to the acoustic quality of spaces, this issue still remains a significant and effective part of any architectural design [13-16].

Due to the great importance of acoustic comfort in therapeutic environments, in recent years, acoustic factors have been given more attention in the architectural design of such spaces. Despite the existing standards and general recommendations, case studies and applied researches are rarely seen. Accordingly, in this research, the study of the real conditions of a common three-bed hospital room in terms of geometry and common materials was considered. To the best of the authors' knowledge, such a study has not been conducted so far.

In the rest of the article, first the key parameters affecting acoustic comfort are introduced. Due to its high importance, the reverberation time is examined in more detail. Next, the modeling and simulation of the hospital room has been discussed. Several options of possible room dimensions as well as common materials are listed. Geometrical acoustic simulations of the room in each of the mentioned cases are carried out in ODEON commercial software. Finally, practical suggestions for choosing room dimensions and materials are provided based on simulation results.

2- Acoustic parameters

The most important parameter investigated in this study is reverberation time. This parameter shows the time required for the sound to decay after the source has been cut off. The reverberation time is indicated by T60 which is the time required for the sound to decrease by 60 decibels after the source has been cut off. In practice, due to the presence of background noises, a 60 dB reduction can be difficult to measure. As a result, other parameters such as EDT, T15, T20 and T30 are also used. Early Decay Time (EDT) is the time required for a 10 dB decrease in the sound intensity while T15, T20 and T30 are the times require for the sound intensity to decrease by 15, 20 and 30 dB, respectively. If the decrease in sound intensity is considered as linear, T60 will be six times larger than EDT, four times larger than T15, three times larger than T20 and twice as large as T30.

However, in practice, the changes deviate from linear pattern [17].

Sound Pressure Level (SPL) is another significant parameters affecting room acoustical behavior. SPL indicates the pressure caused by the soundwaves in an environment. Sound pressure is related to the loudness of the sound but this relation is different for various sound frequencies due to physiological structure of human auditory system. Another parameter is clarity which is defined as two parameters of C50 and C80. This parameter shows the clarity of speech and music in a space. Clarity parameters C50 and C80 are employed as measures of speech clarity and music clarity, respectively.. Another parameter is Lateral Energy Fraction (LEF). This factor measures the ratio of reflected sound energy from side walls to the sound energy from all directions (including direct soundwave coming from the source) present at any point in space. This parameter shows the sound spaciousness of the room and is very important in designing of concert halls. Higher values for this parameter mean that the spaciousness felt by the listener will be larger than the actual spaciousness of the source [17, 18].

Speech transmission index or STI is another parameter which shows the clarity and comprehensibleness of speech. This parameter is calculated for all frequencies and reported as a single number. STI values in the range of 0.6 to 0.75 are considered good, while values between 0.75 to 1 are perfect [19, 20].

3- Importance of Reverberation Time

Reverberation time in a space is directly related to the absorption coefficient of the walls. The reverberation time is calculated using Sabine's equation as shown in equation (1) [21]:

$$T_{60} = \frac{55.25V}{c_0 S_\alpha \bar{\alpha}} \quad (1)$$

In this equation, c0 is the sound speed in air, Sα is the surface area of the absorbent, and V is space volume, which is V=Lx*Ly*Lz for a cubic space. The reverberation time is also related to the number of acoustic modes in the frequency range of interest. The natural frequencies of a cubic space are calculated using equation (2) [20]:

$$f(n_x, n_y, n_z) = \frac{c_0}{2}\sqrt{\left(\frac{n_x}{L_x}\right)^2 + \left(\frac{n_y}{L_y}\right)^2 + \left(\frac{n_z}{L_z}\right)^2} \quad (2)$$

The number of modes which can be excited in this space in the frequency range of 0 to f are calculated using equation (3) [21]:

$$N(f) = \frac{4\pi f^3 V}{3c_0^3} + \frac{\pi f^2 S}{4c_0^2} + \frac{fL}{8c_0} \quad (3)$$

In equation (3), $S=2(L_xL_y+L_xL_z+L_yL_z)$ is the total surface of the room and $L=4(L_x+L_y+L_z)$ is the circumference of the space. Therefore, equation (4) can be stated as follows [21]:

$$\frac{dN}{df} = \frac{4\pi f^2 V}{c_0^3} + \frac{\pi f S}{2c_0^2} + \frac{L}{8c_0} \quad (4)$$

On the other hand, modal density for a cubic space can be estimated using equation (5) [17]:

$$\frac{\Delta N}{\Delta f} = \frac{N(f_{upper}) - N(f_{lower})}{f_{upper} - f_{lower}} \quad (5)$$

Modal overlap, i.e. M, is a criterion used for determining the number of modes in a frequency range and can be computed through equation (6):

$$M = \Delta f \frac{dN}{df} \quad (6)$$

In this relation, Δf=2.20/T60 is the average band width which is a function of reverberation time. Natural frequencies in a room in the hearing range correspond to creating a standing wave at that frequency in the room which is an undesirable event. When selecting the dimensions of a cubic room, the dimensions must be set in a way that the number of these states is minimized. As can be seen from these equations, this is related to the reverberation time of the room. Therefore, reverberation time can be used as the primary criteria for acoustic design.

4- Numerical analysis of acoustics in a sample hospital room

In architectural acoustics, we generally deal with high frequency sound. Therefore, geometrical analysis methods can be adopted with a good approximation. In this article, the commercial geometrical acoustic analysis software, ODEON, is exploited for acoustic analysis of the patient's room.

4-1- The effect of geometrical dimensions and wall materials of hospital room on Reverberation time

In this section, the dimensions of a three-bed hospital room are changed and the effect of this change on the reverberation time of the room is investigated. Frequencies of 500, 1000 and 2000Hz are the most significant center frequencies in terms of hearing. A value around 0.6 seconds is suitable for the average reverberation time of the room for 500, 1000 and 2000Hz frequencies [22]. During the rest of the analysis, the 0.6 second value will be used as the reference value for reverberation time of the hospital room. Table (1) illustrates the simulated rooms' dimensions while Fig. (1) shows the furniture arrangement in a three-bed room. The floor is made of building stone and the walls and ceilings are made from gypsum with a layer of paint. Beds and couches are covered in leather. The window has the dimensions of 2 * 1.6 meters and is made of double glazed glass. In order to investigate the geometrical dimensions, two parameters of aspect ratio (the ratio of length to width) and room volume are considered.

Table 1: Dimensions of the room simulated in ODEON software

Length (m)	Width (m)	Aspect ratio	Area(m^2)	Volume (m^3)
5.1	3.9	1.3077	19.89	59.67
5.1	9.3	0.5484	47.43	142.29
6.3	6.1	1.0328	38.43	115.29
7.1	3.5	2.0286	24.85	74.55
7.3	3.9	1.8718	28.47	85.41
7.3	7.3	1.0000	53.29	159.87
8.3	6.1	1.3067	50.63	151.89
9.8	3.9	2.5128	38.22	114.66
11.1	6.3	1.7619	69.93	209.79

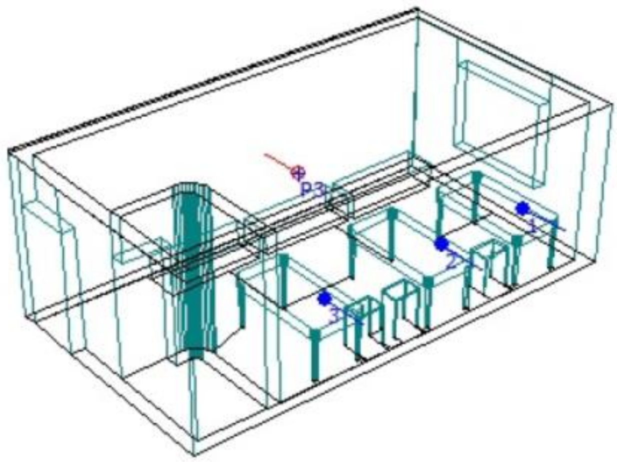

Fig. 1 The furniture layout in a three-bed room with dimensions of 3.5*7.1

4-2- Effect of aspect ratio on reverberation time

Fig. (2) shows the reverberation time calculated in ODEON software for various frequencies in terms of aspect ratio. As can be seen, among the suggested room dimensions (assuming fixed building materials), the aspect ratio of 2.03 shows the best results which belongs to the room with dimensions of 3.5*7.1 meters. The values related to the frequency of 8000Hz in this graph are significantly lower than the values for other frequencies. This is due to significant increase in absorption coefficient at higher frequencies which leads to decrease in reverberation time. This is the dominant effect at the frequency of 8000Hz (compared to the room dimensions) as seen in the graph. In order to carry out a more accurate comparison with the reference values, the average reverberation times at frequencies of 500, 1000 and 2000Hz are calculated and presented in Fig. (3). The results shown in Fig. (3) also confirm the previous results.

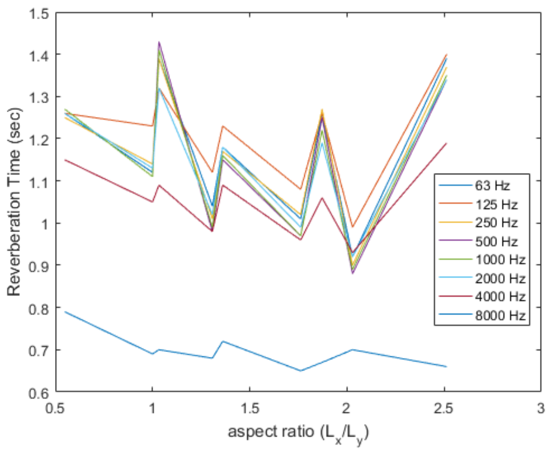

Fig. 2 The Reverberation time for different frequencies based on rooms' aspect ratio

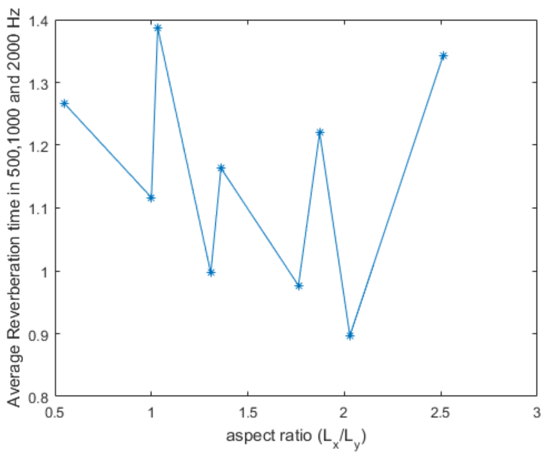

Fig. 3 Average reverberation time at frequencies 500, 1000 and 2000Hz based on rooms' aspect ratio.

4-3- Effect of volume on reverberation time

The calculated reverberation times for the rooms detailed in table (1) based on room volume and different frequencies are presented in Fig. (4). While considering the best possible reverberation time for different frequencies (except for 8000Hz), the room with the volume of 74.6 cubic meters is the best choice. According to table (1), it can be seen that this is the room with the dimensions of 7.1*3.5 meters. The explanation given about the frequency of 8000 Hz in the previous section can be repeated here as well. The changes in average reverberation time at three different frequencies of 500, 1000 and 2000Hz in terms of room volume is shown in Fig. (5). The best reverberation time observed in graphs (3) and (5) is about 0.89 seconds which belongs to the room with dimensions of 7.1*3., with stone floor and celling and walls made of gypsum with a layer of paint. This value is more than 40% higher than the reference value, although the reference value of 0.6 s is a bit optimistic.

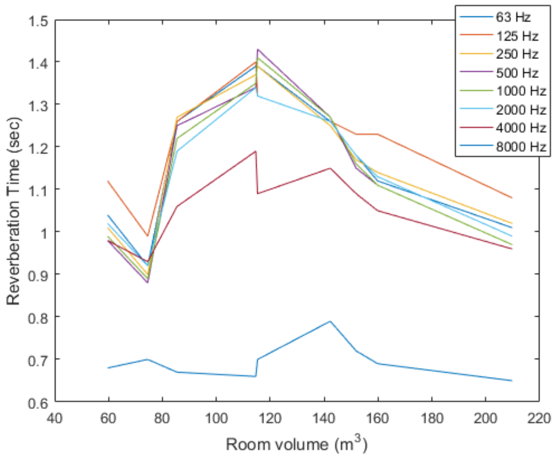

Fig. 4 The changes in reverberation time at different frequencies based on room volume

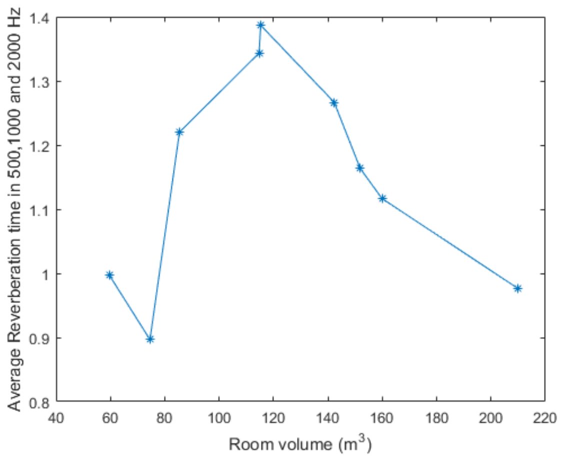

Fig. 5 Average reverberation time at frequencies 500, 1000 and 2000Hz based on room volume

4-4- The effect of material of internal walls on reverberation time

In this section, by considering the best geometrical dimension of the room (7.1m*3.5m), the effect of changes on wall materials on reverberation time is investigated. The room floor is often made of stone while walls can be made from painted vinyl or gypsum. The simulation results for each of these conditions are explained in the following section. Fig. (6) shows the reverberation time of rooms at different frequencies. According to these results, using vinyl walls and ceilings leads to significant reduction in reverberation time compared to the reference value. Stone and gypsum walls have nearly identical behavior but the reverberation time for gypsum walls is closer to the reference value. In order to perform a quantitative comparison between calculated and standard reverberation times, the average reverberation time values were calculated for frequencies of 500, 1000 and 2000Hz and are presented in Fig. (7). The deviation of reverberation time from standard value for stone, gypsum and vinyl walls is equal to 47%, 43% and 10%, respectively. Therefore, vinyl walls leads to the best possible reverberation time for the room.

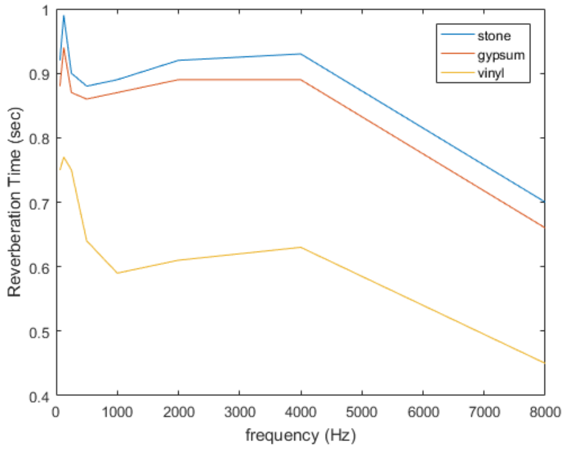

Fig. 6 The Reverberation time values at different frequencies for different building materials.

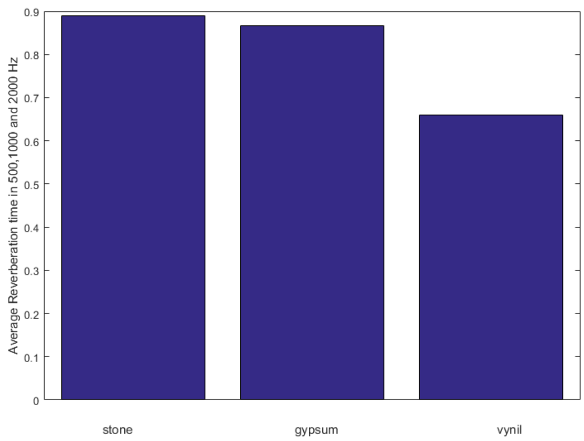

Fig. 7 Average Reverberation time at frequencies 500, 1000 and 2000Hz for different building materials

4-5- Effect of geometrical dimensions and wall materials on clarity (C50) parameter of the hospital room

Room dimensions and wall materials were changed in a similar manner as previous sections. Due to the physiological makeup of human ear, after a sound wave reaches the ear, sound reflections up to 50ms after the arrival of the main wave can improve the clarity of hearing. Any later reflections, on the other hand, have negative effects on hearing clarity. This time delay is equal to 80ms for music sounds. Therefore, speech clarity parameter C_{50} is defined as follows [23]:

$$C_{50} = 10 \log \frac{\text{Energy } (0 - 50 \text{ ms})}{\text{Energy } (50 \text{ ms} - \text{end})} \quad (7)$$

Figs. (8) and (9) show the C_{50} values for different room dimensions in terms of aspect ratio and volume.

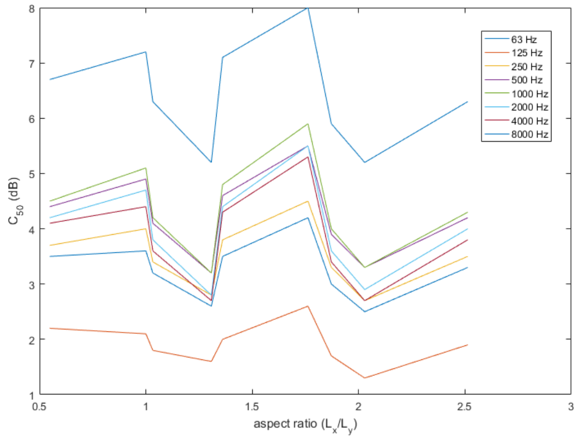

Fig. 8 Sound clarity parameter value at different frequencies based on room's aspect ratio

Fig. (9) shows an almost linear relation between room volume and speech clarity while Fig. (8) indicates a more complex relation. However, the best speech clarity values in both correspond to the room with dimensions of 11.1m*6.3m.

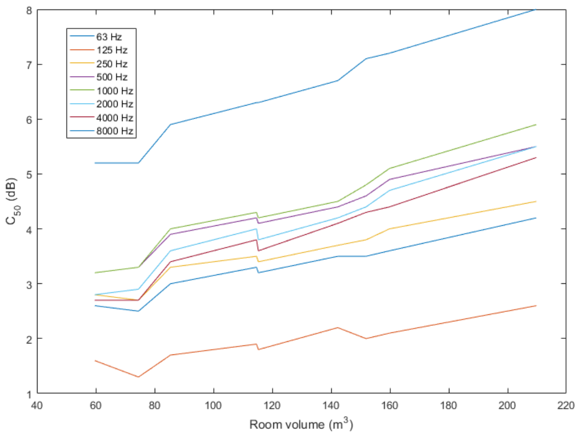

Fig. 9 The values for clarity parameter at different frequencies based on room volume

Another important conclusion is that, speech clarity is better for higher frequencies. Sound speed in air has a very small dependence on frequency [24]. Therefore, variability in speech clarity at different frequencies is due to sound absorption characteristics, which are highly frequency dependent. Since three frequency bands of 500, 1000 and 2000Hz have the highest priority in speech spectrum, results of these three frequencies are presented in Fig. (10). In order to determine the effect of building materials on speech clarity, the optimum room (based on reverberation time) was again used. Fig. (11) shows the changes in speech clarity parameters for three wall materials of stone, gypsum and vinyl. As can be seen in Fig. (11), based on the speech clarity parameter, vinyl has the best performance among all building materials. However, generally, the acoustic importance of reverberation time in a medical environment is higher that speech clarity while this priority might be reversed in other applications such as conference halls or classrooms.

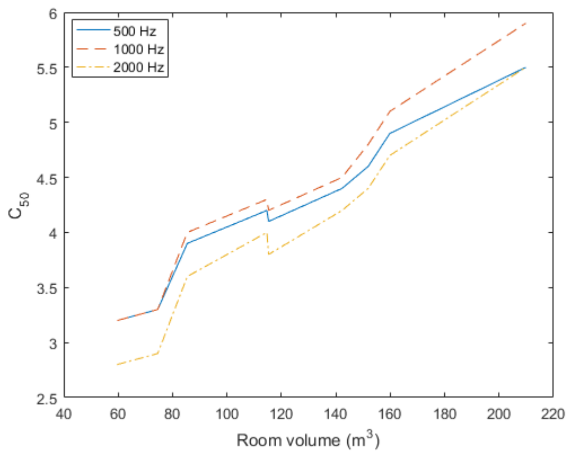

Fig. 10 The speech clarity parameter values at frequencies 500, 1000 and 2000Hz based on room volume

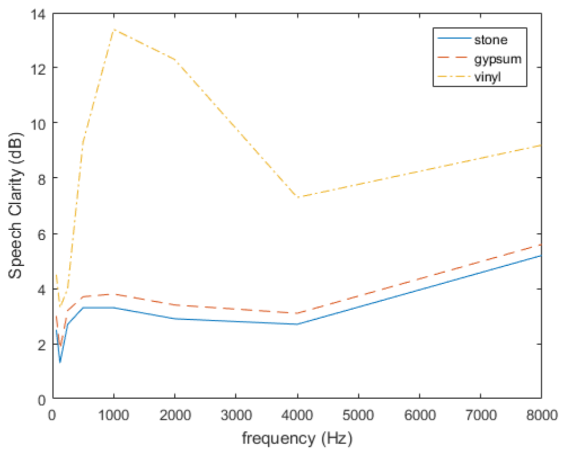

Fig. 11 Speech clarity values at different frequencies for different building materials

5- Conclusion

The aim of this study was to investigate the effect of geometry and wall materials on acoustic properties of hospital rooms. Two parameters were used for this purpose including reverberation time and speech clarity. Rooms with areas in the range of 20 to 70 square meters were simulated as three-bed hospital rooms in ODEON software. Under each set of conditions, the layout of a three-bed room including patient beds and couches for visitors was considered. The volume and aspect ratio of the rooms were used to evaluate the effect of geometry on acoustics. Based on the limitations on the permitted building materials for medical spaces, three common allowed materials including gypsum, stone and vinyl were used for the internal surfaces of the rooms. By considering the reference value of 0.6 seconds for reverberation time at frequencies of 500, 1000 and 2000Hz in hospital room, among various simulated room dimensions, the room with dimensions of 7.1m*3.5m has the closest reverberation time to the reference value from both volume and aspect ratio perspectives.

References

[1] Rangga, F. et al. (2024). Hospital interior design with healing environment approach. in *AIP Conference Proceedings*. AIP Publishing.

[2] Raghuwanshi, N.K. et al. (2024). Noise effects, analysis and control in hospitals-A review. *Noise & Vibration Worldwide*, 09574565241235326.

[3] Bliefnick, J.M., Ryherd, E.E. and Jackson R. (2019). Evaluating hospital soundscapes to improve patient experience. *The Journal of the Acoustical Society of America*. 145(2). 1117.

[4] Jerlehag, C. et al. (2018). Acoustic environments of patient room in a typical geriatric ward. *Applied Acoustics*. 133. 186-193.

[5] Montes-González, D. et al. (2019). Environmental Noise around Hospital Areas: A Case Study. *Environments*. 6(4). 41.

[6] Adams, C. et al. (2024). As loud as a construction site: Noise levels in the emergency department. *Australasian Emergency Care*. 27(1). 26-29.

[7] Wang, T.C. et al. (2024). Impact of occupational noise exposure on the hearing level in hospital staffs: a longitudinal study. *Environmental Science and Pollution Research*. 1-10.

[8] Chen, C. Y. (2015). Characterizing Subjective Noisiness in Hospital Lobbies. *Archives of Acoustics*. 40(2). 235-246.

[9] Hill, J.N. and LaVela, S.L. (2015). Noise Levels in Patient Rooms and at Nursing Stations at Three VA Medical Centers. *Herd*. 9(1). 54-63.

[10] Xie, H., Kang, J. and Mills G.H. (2009). Clinical review: The impact of noise on patients' sleep and the effectiveness of noise reduction strategies in intensive care units. *Critical Care*. 13(2). 208.

[11] Mommersteeg, B. (2024). Approximations: On some ways to listen to a building “in the making”. *Science, Technology, & Human Values*. 49(2. 238-262.

[12] Herman, M. and Saragih, J.B. (2024). Spatial Acoustic Approach: Sustainable Design Methods in Creative Centre Building. in *IOP Conference Series: Earth and Environmental Science*. IOP Publishing.

[13] Coffeen, R.C. (2012). Techniques for teaching building acoustics and noise control to university architecture students. *The Journal of the Acoustical Society of America*. 132(3). 1922-1922.

[14] Lokki, T. and Pätynen, J. (2019). Architectural Features That Make Music

Bloom in Concert Halls. *Acoustics*. 1(2). 439-449.

[15] Peters, B. (2015). Integrating acoustic simulation in architectural design workflows: the FabPod meeting room prototype. *SIMULATION*. 91(9). 787-808.

[16] Shield, B.M. and Dockrell, J.E. (2003). The Effects of Noise on Children at School: A Review. *Building Acoustics*. 10(2). 97-116.

[17] Cavanaugh, W.J. (2009). *Architectural Acoustics: Principles and Practice, 2nd Edition*. John Wiley & Sons.

[18] Ellingson, R.M., Gallun, F.J. and Bock, G. (2015). Measurement with verification of stationary signals and noise in extremely quiet environments: Measuring below the noise floor. *The Journal of the Acoustical Society of America*. **137**(3). 1164-1179.

[19] jedidi, M. (2016). Acoustic Study of an Auditorium by the Determination of Reverberation Time and Speech Transmission Index. *IUST*. 26(1). 25-32.

[20] Soha Eldakdoky, A.E. (2017). Acoustic improvement on two lecture auditoria: Simulation and experiment. *Frontiers of Architectural Research*. 6(1). 1-16.

[21] Howard, C.Q. and Cazzolato, B.S. (2017). *Acoustic analyses using Matlab and Ansys*. Boca Raton: CRC Press.

[22] Ermann, M. (2015). Architectural acoustics illustrated. *The Journal of the Acoustical Society of America*. 137(4). 2358-2358.

[23] Nyembwe, J.P.K.B. et al. (2023). Evaluation of Noise Level in Intensive Care Units of Hospitals and Noise Mitigation Strategies, Case Study: Democratic Republic of Congo. *Buildings*. 13(2). 278.

[24] Swanson, D.C. (2010). *Architectural Acoustics: Principles and Practice, 2nd ed.* John Wiley & Sons Press.