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A Study on the Redesign of Hospital Outpatient Halls Based on Acoustic Environment Requirements

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Abstract

The acoustic design of outpatient halls is often ignored, yet the acoustic environment significantly impacts patients' physical and mental well-being as well as their visit experience. This paper takes the outpatient hall of a hospital in South China as a case, employs in-situ acoustic measurement, and conducts a quantitative analysis of its indoor acoustic environment through acoustic simulation. The in-situ measurements show that the noise level, speech intelligibility and reverberation time in the hall all fail to meet standard requirements. The poor acoustic quality is mainly due to the lack of acoustic design. Consequently, this study proposes measures to improve the outpatient hall's acoustic environment from two aspects, namely sound absorption and building form design. These measures include sound absorption treatment, adjustment of the hall's floor height and optimization of planar length-to-width ratio. The redesigned outpatient hall plan demonstrates an evident enhancement in acoustic quality and validates the effectiveness of the proposed redesign strategy. This study can provide practical guidance for the design and acoustic renovation of healthcare buildings and can also offer new insights for the redesign of hospital outpatient halls from the perspective of improving the acoustic environments.

Keywords: outpatient hall; redesign; acoustic environment quality; noise control; speech intelligibility

1. Introduction

With the increasing demand for public health, the number of medical institutions is steadily rising. In China, the number of hospitals has grown to 38,355 [1]. To promote patients' recovery, hospitals must not only provide high-quality medical services but also create a healthy and comfortable environment. As a crucial component of the hospital environment, the importance of the acoustic environment has become more and more prominent [2,3]. For a long period, public attention focused more on the quality of medical care. The effect of acoustic environment on patients' physiological and psychological well-being is ignored. Noise pollution has become the second most significant environmental threat after air pollution [4] and is regarded as the primary concern of hospital environments [5]. Noise level in hospital buildings increased at an average rate of 0.38 dB annually [6]. A deteriorated acoustic environment, especially high noise levels, may induce the patients' anxiety [7], accelerate heart rate and increase blood pressure [8], and hinder recovery progress [9]. It increases analgesic dosages, readmission rates, and prolongs hospital stays [10]. Noise also causes anxiety, psychological and physiological fatigue

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among medical staff, thereby reducing the quality of medical services [11]. Additionally, indoor noise impairs speech communication [12,13].

Currently, the improvement of the acoustic environment quality in hospitals has become an international consensus. Some countries and organizations have established their own acoustic standards or codes to guide their hospital design. For example, the WHO's Community Noise Control Guidelines stipulate that L_{Aeq} at night should not exceed 30 dB and the maximum continuous A-weighted sound level L_{Amax} should not exceed 40 dB in hospital wards [14]. The United States, the United Kingdom, and China have also proposed their standards, respectively [15–17]. The UK's HTM 08-01 standard stipulates that the $L_{Aeq,1h}$ in hospital circulation spaces should not exceed 55 dB. The $L_{Aeq,1h}$ in open clinical areas should not exceed 45 dB [16]. According to China's GB 50118-2010 [17], hospitals are required to implement sound absorption measures. The Noise Reduction Coefficient (NRC) of the ceiling finish is no less than 0.4, and indoor reverberation time is below 2 s. However, these standards or codes consider only the acoustic environment of the ward, not the acoustic environment in the public space, such as the outpatient hall. The acoustic evaluation index is a single one and only analyzes the influence of noise level on the acoustic environment. It does not investigate the influence of other parameters, such as speech transmission index (STI) and reverberation time (T_{30}). Therefore, comprehensive analysis of the acoustic environment quality of the public space is lacking. During a hospital visit, the outpatient hall is the first public space that patients enter. It integrates multiple functions such as inquiries, medicine pickup, registration, and payment; it is easy to cause people congestion and traffic chaos as shown in Figure 1. Field surveys indicate that the average time patients linger in the outpatient hall is over 100 min [18]. They become more sensitive to the acoustic environment and are particularly concerned about its quality. However, most existing studies focus on the acoustic environments only in hospital wards [19–22], with little attention given to public spaces like outpatient halls [13,23]. Especially, the research on their acoustic quality and redesign remains scarce.



Figure 1. Crowded outpatient hall with patients waiting.

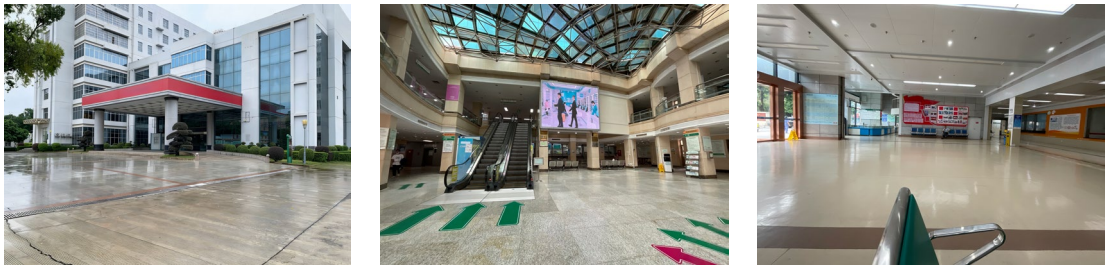
Favorite acoustic environment quality can not only improve the patients' experience but also facilitate their recovery. Improvement of the sound conditions in hospital outpatient halls from the patients' perspective reflects a people-centered care idea. Therefore, it is essential to analyze the current acoustic quality in an outpatient hall, seek its improvement and develop redesign strategies that create a healthy and comfortable environment for patients. The structure of this paper covers the following: Section 1 is the introduction. Section 2 introduces the materials and methodology. Section 3 focuses on analysis of current acoustic environment and improvement measures. According to the acoustic environment

requirements, Section 4 provides the redesign schemes of the outpatient halls and their validation by acoustic simulation. Sections 5 and 6 present the discussion and conclusions drawn from this study, respectively.

2. Materials and Methods

2.1. Architectural Features

The hospital studied here is located in Nanning, a city in southern China characterized by a subtropical monsoon climate with high temperature and humidity. To adapt to this climate, outpatient halls in local hospitals are commonly designed with a large area of glass curtain walls on the facade to enhance transparency and daylighting (Figure 2a), spacious and lofty halls to facilitate air circulation (Figure 2b), and a hard interior finish for ease of cleaning (Figure 2c). However, all these building features may lead to some serious acoustic defects. First of all, there is poor sound insulation due to thin and light exterior walls and large areas of glass curtain walls. Consequently, the outpatient hall is more vulnerable to outdoor noise, which enhances the indoor noise level. Additionally, the high indoor space and interior hard finishes prolong the reverberation time and impair speech intelligibility. Furthermore, the field surveys also identify that there are some acoustic defects such as high noise level and difficulties in speech communication in the halls.



(**a**) (**b**) (**c**)

Figure 2. The hospital in Southern China: (**a**) façade with glass curtain wall; (**b**) spacious and lofty halls; (**c**) hard interior finishes.

Figure 3 introduces the floor plan, section and in-situ photos of the outpatient hall in the case-study hospital. In Figure 3a, the gray area represents the outpatient hall. For ease of drawing, the undulating walls in the entrance area are simplified in the floor plan. However, the simulation model used for subsequent analysis fully covers these details. Its floor plan is approximately rectangular, with an area of about 695.57 m^2 and a volume of approximately 4823.8 m^3. The hall mainly serves functions such as inquiries, medicine pickup, registration and payment. The blue area in Figure 3a represents a rectangular corridor, with an approximately 39.8 m^2 area and floor height of 3.2 m, as shown in Figure 3b. The pink area in Figure 3a shows a waiting area with an area of about 40.3 m^2, as shown in detail in Figure 3c. Interior walls and floors are decorated with ceramic tiles, while the ceiling is plastered. As illustrated in the section view in Figure 3d, the hall maintains a consistent floor height along the north–south direction. Above it, the waiting area on the second floor is coupled with the hall through an opening.

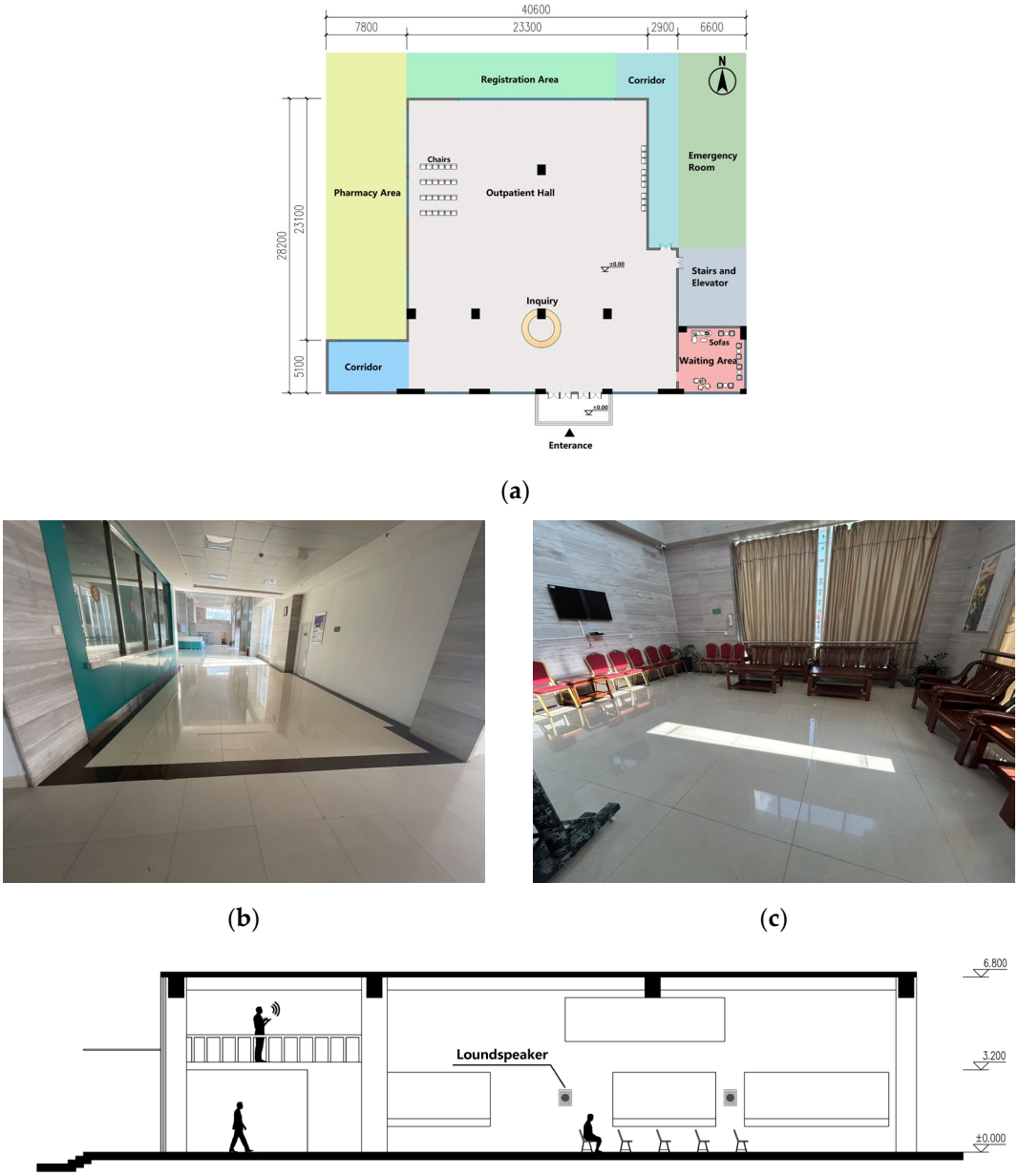


Figure 3. The outpatient hall: (**a**) floor plan; (**b**) corridor on the left of the plan; (**c**) rectangular area on the right; (**d**) section.

2.2. Acoustic Evaluation

To accurately evaluate the acoustic environment quality of hospital outpatient halls, it is necessary to find an appropriate evaluation index. Field investigations reveal that the patients suffer from acoustic defects such as high noise level, poor speech intelligibility, unclear public announcements, and echoes in the outpatient halls. Therefore, three acoustic parameters, noise level (L_A), speech transmission index (STI) and reverberation time (T_{30}), are taken as the indices to assess acoustic environment in the halls.

The A-weighted sound pressure level L_A is a predominant acoustic parameter to evaluate acoustic environment and can be expressed as

$$L_A = L_{50} + \frac{(L_{10} - L_{90})^2}{60} \quad (1)$$

where L_{10}, L_{50} and L_{90} represent the peak noise level, the average noise level and the background noise level separately. High noise level not only abates speech intelligibility [24] but also increases patients' annoyance.

Based on the in-situ measurement and survey, in the outpatient hall, the noise levels exhibits somewhat stable, without strong fluctuation; the environment belongs to public or semi-public space. The conversations between patients and staff generally refer to inquiries about department locations, which do not involve private information such as specific illness conditions. Noise reduction and articulation is the primary issue in this kind of space. Therefore, high speech intelligibility is essential for patients and staff to ensure accurate and clear communication. Speech intelligibility is evaluated by *STI*, whose values range from 0 to 1. The higher the *STI*, the clearer the speech. *STI* can be measured by direct and indirect methods [25]. Compared with the direct method, the indirect method, which is based on the indoor impulse response, requires less measurement time and is often used in indoor acoustic measurement [26]. Its procedure is as follows: the indoor impulse response should be measured first, and then the Modulation Transfer Function (*MTF*) can be calculated as

$$m_k(f_m) = \frac{\left|\int_0^\infty h_k^2(t)e^{-j2\pi f_m t}dt\right|}{\int_0^\infty h_k^2(t)dt} \times \left(1 + 10^{-SNR_k/10}\right)^{-1} \quad (2)$$

The k means the number of octave bands; f_m denotes the modulation frequency; t is the integration time; $h_k(t)$ is the impulse response of kth octave bands; and *SNR* is the signal-to-noise ratio for kth octave bands. According to IEC 60268-16:2020 [27], the *STI* is

$$STI = \sum_{k=1}^{7} \alpha_k \times MTI_k - \sum_{k=1}^{6} \beta_k \times \sqrt{MTI_k \times MTI_{k+1}}, \quad (3)$$

where *MTI* is the Modulation Transfer Index for kth octave bands; α_k is the weighting factor for kth octave bands; and β_k is the redundancy factor between the kth and $(k + 1)$th frequency bands across both genders.

Table 1 shows a five-level evaluation scale correlating *STI* values with subjective speech intelligibility provided by IEC 60268-16:2020 [27]. As a public space designed for speech communication, the outpatient hall requires a minimum *STI* of 0.45 to ensure effective speech communication.

Table 1. Relationship between *STI* and subjective speech intelligibility according to IEC 60268-16:2020.

Subjective Speech Intelligibility	Bad	Poor	Fair	Good	Excellent
STI	<0.30	0.30–0.45	0.45–0.60	0.60–0.75	>0.75

Reverberation time T_{60} is a key parameter for acoustic design. It depends on the rate of sound energy decay within a room and denotes the time required for the steady-state noise level to decay to 60 dB of its original value after the sound ceases. The reverberation time T_{60} can be expressed as

$$T_{60} = \frac{0.161V}{-S\ln(1-\bar{\alpha})} \quad (4)$$

where the V is the volume of the room; S is the internal surface area of the room; and $\bar{\alpha}$ presents the average sound absorption coefficients.

Due to the presence of background noise and low signal-to-noise ratio, it is usually impractical to achieve a full 60 dB decay. Therefore, in practical research and engineering applications, the reverberation time is determined by multiplying the time required for the attenuation of noise level by 30 dB and 2, denoted as T_{30}.

These three parameters can reflect the acoustic environment quality of the outpatient hall in terms of noise level, speech intelligibility and sound energy decay separately.

2.3. Measurements

In-situ measurements were conducted using the Casella CEL-240 sound level meter and SONY ICD-PX470 sound recorder to assess the existing acoustic situation in the hall. The sound level meter has a measurement range of 30 to 130 dB RMS with an accuracy of ±0.1 dB, while the sound recorder covers a frequency range of 50 to 20,000 Hz. The specifications of these devices are summarized in Table 2. To ensure reproducibility and measurement accuracy, before each measurement, the sound level meter was calibrated by an acoustic calibrator (B&K 4231), which generates a 94 dB signal at 1000 Hz. The impulse response measurements were conducted during the noon period on weekends when patient numbers were low. The background noise during this period was approximately 41 dB. In the scenario of in-situ measurement, the most concern of selecting a pulsed sound source lies in its signal-to-noise ratio (*SNR*), which, in the case of a balloon bursting in the outpatient hall, can exceed 35 dB. However, this kind of method has some limitations in repeatability, directivity and spectral content, given the constraints of experimental devices and the sensitive environment of the hospital. So, balloon pops can be taken into an appropriate measurement approach in the public building space.

Table 2. The specification of the measurement devices.

Device	Make	Model	Data	Range	Accuracy
Sound level meter	Casella	CEL-240	L_A	30–130 dB RMS	±0.1 dB
Sound recorder	SONY	ICD-PX470	Impulse response	50–20,000 Hz	–

In Table 2, the measurement devices and their specifications are listed. The indoor impulse responses of the hall are read three times at each measuring point by a digital audio recorder; then, *STI* and T_{30} were obtained through the impulse response analysis [28]. Subsequently, the sound level meter was employed to measure the L_A.

Figure 4 illustrates the distribution of measurement points as well as in-situ photos of the measurement process. In accordance with the measurement standard of ISO 3382-2:2008 [29], 14 measuring points are evenly distributed over the floor plan of the hospital outpatient hall. These points cover main functional areas such as the pharmacy, registration, inquiry, and random areas, as shown in Figure 4a. Each receiving point, which is denoted as R, is 1.2 m high above the floor and no less than 1.5 m away from any wall or obstruction. The sound source point S, where the balloons were burst to generate an impulse response, is 1.5 m above the floor and located in the center of the hall. Table 3 summarizes the relative positions between sound source point S and all receiving points R, as well as the functional zone to which each receiving point belongs. During the measurement period, the size of balloons and each puncture are kept as consistent as possible. Figure 4b shows the scene of recording impulse responses at a receiving point. Then, T_{30} and *STI* were calculated by Dirac software. The indoor noise level L_A and background noise were measured by the A-weighted mode of a meter during the hospital's peak time on weekdays and during the quieter midday on a weekend, respectively. As the hospital was in operation during the measurement, the noise level was only recorded for a certain period. Data were recorded every five seconds; then, 200 data points were collected. The equivalent continuous A-weighted sound pressure level (L_{Aeq}) was calculated based on Equation (1).



(**a**) (**b**)

Figure 4. Acoustic measurements: (**a**) distribution of measuring points; (**b**) in-situ measurement photo.

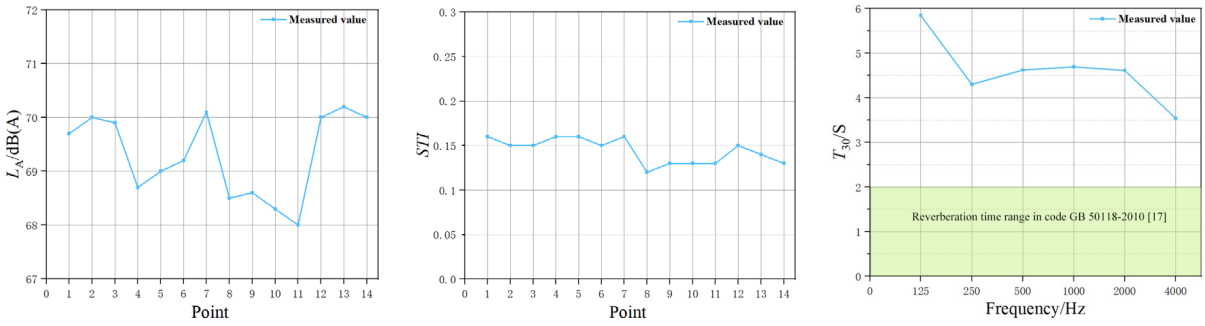
Table 3. Relative positions between sound source point S and all receiving points R.

Belongs to Which Functional Area	Receiving Points	Sound Source Point-Receiving Point Distance (m)
Pharmacy area	R1, R2, R3, R7	6–9–11–10
Registration area	R12, R13, R14	14–12–11
Inquiry area	R4, R9, R10	5–12–11
Random area	R5, R6, R8, R11	6–10–15–14

3. Acoustic Environment and Its Improvement Measures

3.1. Measurement

Figure 5a presents the measured L_A in the outpatient hall. It ranges from 68 dB to 70 dB and far exceeds the national standard requirement of 55 dB [17]. This is due to the lack of acoustic design and functional zoning. When the patients register or pick up their medicine, they gather in the registration area and pharmacy area for a long time. Then, people congestion occurs. Consequently, the concentration of their speech sound generates an evident Lombard effect, which further deteriorates the acoustic environment in the hall.



(**a**) (**b**) (**c**)

Figure 5. Measured results in hospital outpatient hall: (**a**) L_A; (**b**) *STI*; (**c**) T_{30}.

The measured *STI* in the hall ranges from 0.12 to 0.16 as shown in Figure 5b. Its average value in all receiving points is merely 0.14, far from meeting the standard requirement of $STI \geq 0.45$. Therefore, patients may experience poor speech intelligibility during their stay in the hall.

The measured reverberation time T_{30} varies as shown in Figure 5c. It fails to meet the required standards over the whole frequency range, with high T_{30} at low frequencies and low T_{30} in the middle and high frequencies. It results from the large volume of the

outpatient hall and the hard finish of each interior surface, which leads to the sound absorption being insufficient. Apart from these, parallel east and west walls may produce flutter echoes.

In an outpatient hall, the in-situ acoustic measurements indicate that patients often suffer from serious acoustic defects, such as high noise level, unclear speech and long reverberation time. Consequently, its acoustic environment quality needs to be improved.

3.2. Acoustic Improvement Measures

3.2.1. Simulation Analysis

For the outpatient hall's acoustic environment, it is necessary to propose corresponding improvement measures to mitigate or eliminate their acoustic defects. For further quantitative analysis, a simulation model was established by Odeon software. Odeon, developed by the Technical University of Denmark, is an acoustic simulation software that employs virtual sound source and ray tracing approaches [30]. Its high simulation accuracy has made it widely used in both indoor acoustic design for various kinds of buildings [31,32] and outdoor acoustic environment prediction [33,34].

Based on the hall's plan and section shown in Figure 3a,d, a simulation model was developed as depicted in Figure 6. The sound absorption coefficients of each internal surface are listed in Table 4 [35]. These coefficients were then assigned to the corresponding surfaces in the model. Meanwhile, the frequency spectra of various sound sources were defined based on measured octave-band data, as listed in Table 5. Since the actual measurement environment is complex, some details in the model are simplified. Therefore, the simulation process relies on an idealized environment. The key modeling parameters are set as follows: reflection order is 2, the number of rays is 4000, the calculation grid size is 0.5 m, the scattering coefficient is 0.05 and the occupancy condition is 1/3 as the daily survey.

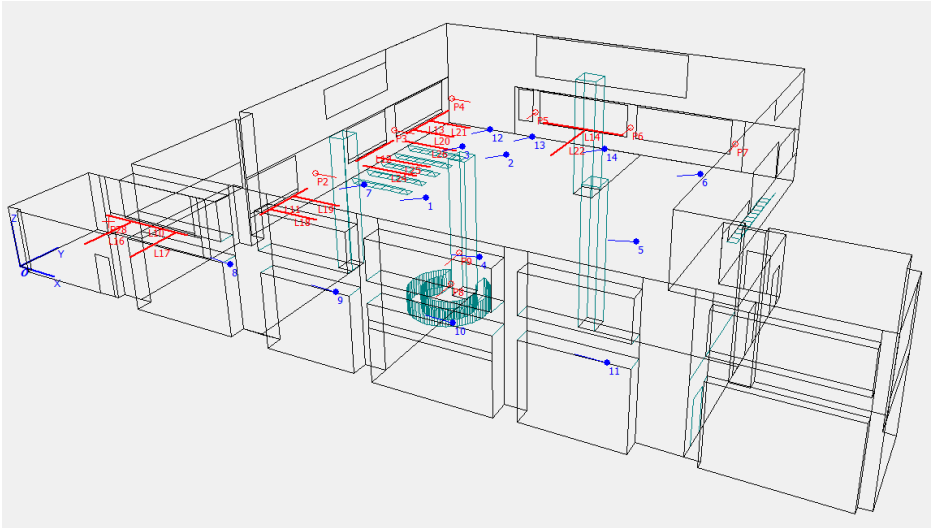


Figure 6. Odeon model of the outpatient hall.

Consequently, specific acoustic improvement measures are proposed: sound absorption treatment, adjustment of the hall's floor height and optimization of planar length-to-width ratio. Through the analysis of the hall's simulation model, the impact of these measures on the acoustic environment is quantitatively analyzed from two perspectives: the indoor sound absorption treatment and form design.

Table 4. Sound absorption coefficients of interface materials in the simulation model.

Name of Material	Frequency/Hz					
	125	**250**	**500**	**1000**	**2000**	**4000**
Glass	0.35	0.25	0.18	0.12	0.07	0.04
Electronic screen	0.1	0.1	0.35	0.5	0.35	0.04
Plaster	0.03	0.03	0.03	0.04	0.05	0.07
Wooden doors	0.18	0.15	0.1	0.1	0.1	0.1
Plywood	0.1	0.1	0.12	0.2	0.12	0.02
Aluminum plate	0.01	0.01	0.01	0.02	0.02	0.02
Metal seats (occupied)	0.16	0.2	0.31	0.38	0.46	0.4
Ceramic tiles	0.01	0.01	0.01	0.01	0.02	0.02

Table 5. The frequency spectra of the sound sources in the 1/2 octave band.

Name of Source	Frequency/Hz					
	125	**250**	**500**	**1000**	**2000**	**4000**
Consultation speech	37.9	51.9	58.9	61.4	56.4	49.3
Public announcement	51	69	70.4	74.3	72.8	72.4
Window counter speech	43.4	55.8	69.9	69.2	63.4	57.4
Seated conversation	37.9	51.9	58.9	61.4	56.4	49.3
Queuing speech	42.6	55.1	63.3	62.6	58.9	52.7

3.2.2. Sound Absorption Treatment

Sound absorption treatment involves the option of sound absorption configuration, the placement of sound absorption material and the determination of sound absorption area. Based on the actual conditions of the interior surfaces in an outpatient hall, three sound absorption schemes are proposed: spray the 16 mm thick K-13 sound absorption coating material over the ceiling, install the perforated aluminum plates on the ceiling, and place the perforated gypsum plate on the side walls. K-13, which is made from natural plant fibers, is a high-performance sound absorption material. It exhibits superior sound absorption in the middle and high frequency ranges and also offers thermal insulation, fire resistance and eco-friendliness. Thus, it is widely used as a method for noise control in indoor spaces [36]. Its detailed configuration is shown in Figure 7a. The perforated plate in Figure 7b represents a resonant sound absorption configuration with a high sound absorption coefficient at low frequencies. When its cavity is filled with glass wool, the high sound absorption performance will extend to the high frequency range. It means that the frequency range of effective sound absorption is expanded. Figure 7c shows the sound absorption configuration of the perforated plate on the side wall. Tables 6 and 7 list sound absorption coefficients of these configurations [35] and their placement. From the perspective of architectural design, given the thickness of the perforated aluminum plates used in Scheme 2, this sound absorption configuration was not placed on the ceiling of the rectangular corridor (blue area in Figure 3a) to avoid excessively low floor height. Consequently, the treatment area differs by 39.8 m^2 between Scheme 1 and Scheme 2.

Figure 8a illustrates the noise levels in different sound absorption schemes. After sound absorption treatments of Schemes 1, 2, and 3, the indoor noise level L_A decreases from 69.3 dB to 63.6 dB, 64.5 dB, and 67.9 dB, respectively. Although the indoor noise level reduces remarkably, it does not meet the standard requirement of 55 dB eventually.

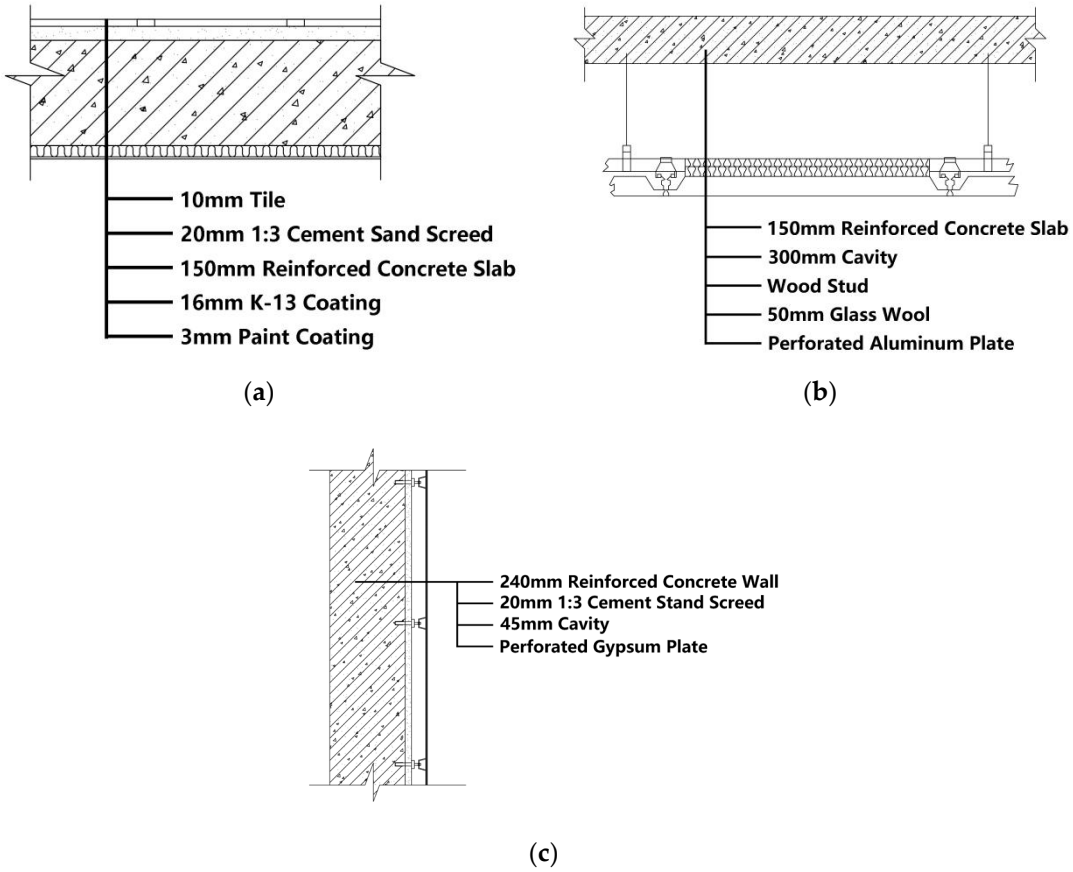


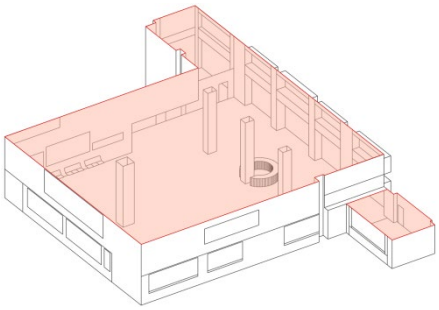
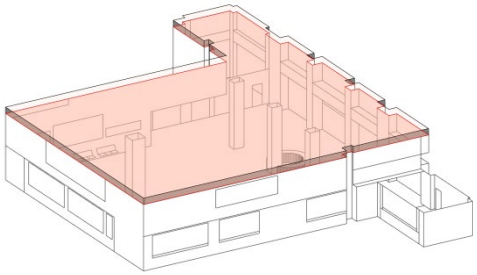
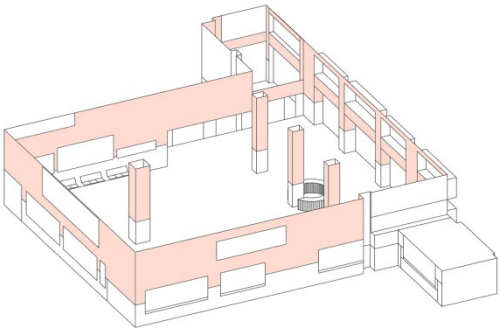
Figure 7. Three kinds of sound absorption configurations: (**a**) 16 mm thick K13 coating material on ceiling; (**b**) perforated aluminum plate on ceiling; (**c**) perforated gypsum plate on side wall.

Table 6. Sound absorption coefficients of each configuration.

Treatment Location	Name of Materials	Frequency/Hz					
		125	**250**	**500**	**1000**	**2000**	**4000**
Ceiling	16 mm thick K-13 coating	0.05	0.16	0.44	0.79	0.9	0.91
Ceiling	Perforated aluminum plates with glass wool	0.35	0.6	0.6	0.65	0.7	0.75
Side wall	Perforated gypsum plates	0.27	0.51	0.28	0.34	0.28	0.32

Figure 8b compares the *STI* of three sound absorption schemes. After treatment, the average *STI* of Schemes 1, 2, and 3 increases from the original 0.14 to 0.39, 0.40, and 0.32 respectively. Notably, the *STI* at the receiving points near the sound sources is higher than those of the receiving points farther away. Therefore, in the outpatient hall, appropriate sound absorption schemes are determined according to crowd distribution in different zones. For instance, if more patients gather near the registration and the pharmacy areas, there is loud noise from speech and loudspeaker announcements. So, the noise levels in these areas will be pretty high. Therefore, priority should be given to applying sound absorption treatments to the ceilings and side walls in these areas. As for the quieter areas such as waiting areas, the sound absorption configurations should be placed on the ceiling or side walls of these areas to accommodate the needs of a quiet space and verbal communication.

Table 7. The sound absorption placement.

Scheme	Materials	Treatment Location	Treatment Area (Pink Area)	Layout Diagram
1	K-13 coating	Ceiling	775.67 m^2	
2	Perforated aluminum plate	Ceiling	735.87 m^2	
3	Perforated gypsum plate	Side wall	324.93 m^2	

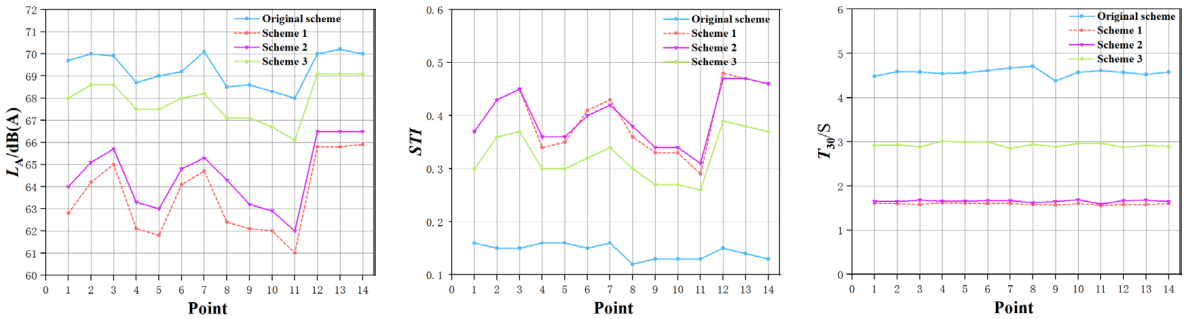


Figure 8. Comparison of results before and after different architectural sound absorption schemes: (**a**) L_A; (**b**) *STI*; (**c**) T_{30} at 500–1000 Hz.

Figure 8c shows the reverberation time T_{30} of the three sound absorption schemes. Schemes 1 and 2 achieve the required T_{30} (500–1000 Hz) of 1.59 s and 1.66 s, respectively, and meet the standard requirements. Scheme 3, however, fails to meet the standard due to insufficient sound absorption area on the side walls, with an average reverberation time of 2.93 s. Although there is a difference in sound absorption coefficient between the K-13 sound absorption coating material and perforated aluminum plate, the reverberation times

of Schemes 1 and 2 yield similar results. Because of the different thicknesses of absorption structures, in practice, the option of structures depends on the indoor floor height of the hall. When the floor height is below 3.6 m, K-13 coating is more suitable; otherwise, both are acceptable. If the perforated aluminum plate configuration is chosen, it provides both comparable acoustic performance and lower decoration cost.

Figures 9–11 present the visual distributions of L_A, *STI*, and T_{30} under the different sound absorption schemes. Figure 9a shows the noise level distribution of the original scheme without sound absorption. In Schemes 1 and 2 represented in Figure 9b,c, the absorption treatments clearly reduce L_A. Only the areas with concentrated sound sources, such as the registration and pharmacy windows area, exhibit relatively high L_A. In contrast, Scheme 3, as shown in Figure 9d, demonstrates marginal noise reduction.

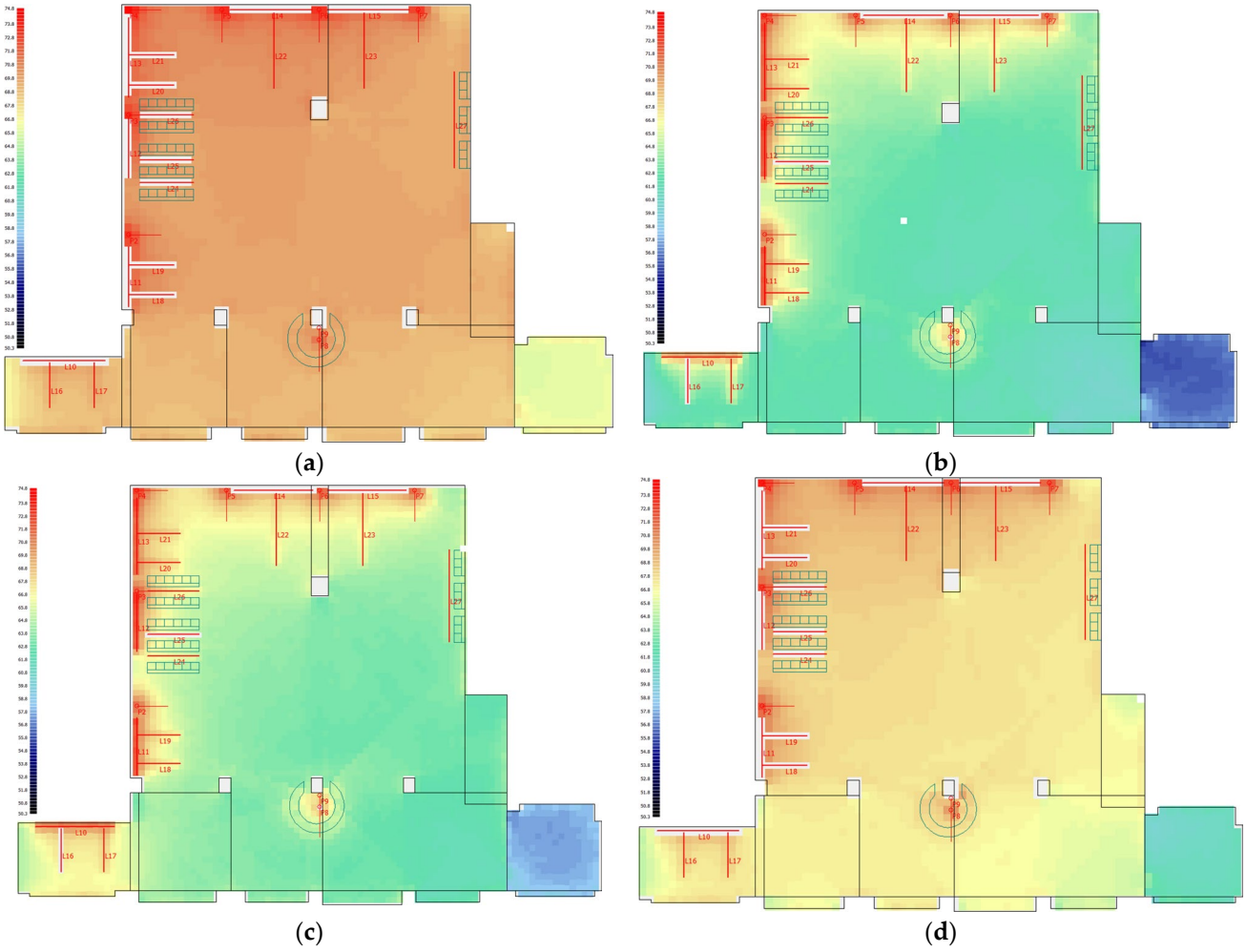


Figure 9. L_A of different schemes: (**a**) original scheme; (**b**) Scheme 1; (**c**) Scheme 2; (**d**) Scheme 3.

The *STI* of the different sound absorption schemes is shown in Figure 10. The distribution of the original scheme is displayed in Figure 10a, where *STI* is generally low. The green color block in the western side of the hall indicates that it has a higher *STI* than the eastern side with blue block because it is near the sound sources. The *STI* in the red-framed area is approximately 0.33, while it is about 0.31 in the yellow-framed area. This variation in speech intelligibility may be related to differences in their floor height. The red-framed area has a floor height of 3.2 m, whereas the yellow-framed area has a height of 6.8 m. The lower floor height in the red-framed area strengthens early reflections from the ceiling, and the rear wall of the rectangular space can also strengthen these reflections. Therefore, speech intelligibility is improved. In Schemes 1 and 2, shown in Figure 10b,c, where sound

absorption is applied to the ceiling, most areas shift from the blue to light blue. It indicates a clear improvement in *STI*. In Scheme 3, furthermore, the *STI* remains relatively low, owing to insufficient sound absorption areas on the side walls.

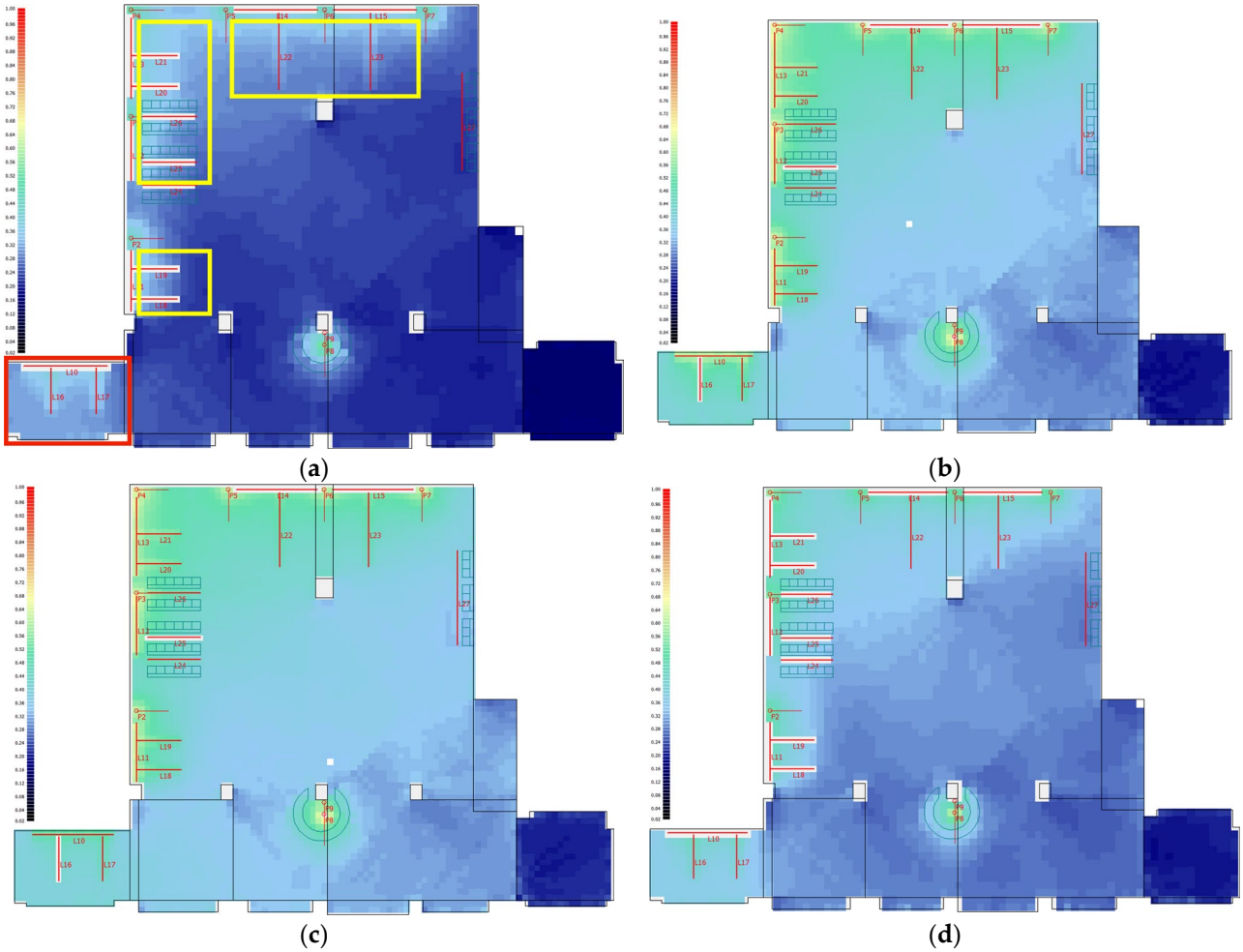


Figure 10. *STI* of different schemes: (**a**) original scheme; (**b**) Scheme 1; (**c**) Scheme 2; (**d**) Scheme 3.

The original scheme is shown in Figure 11a. The reverberation time distribution on the hall plan displays an orange block with a little bit of red, which shows reverberation time is excessively long. Figure 11b–d displays the distributions of reverberation time on the floor plans of Schemes 1, 2, and 3. The color on the plans of these schemes exhibits blue and green, which illustrates a significant reduction in reverberation time after the sound absorption treatments.

The above analysis reveals the effectiveness of the improvement in different sound absorption schemes. The ranking from high to low is as follows: Scheme 1 > Scheme 2 > Scheme 3. The ranking is obtained from direct comparison of the arithmetic means of the acoustic parameters obtained from 14 receiving points for each scheme. As only four design schemes are compared in this study, the limited number of schemes does not allow for statistical testing. Given the large floor area of the outpatient hall, the ceiling has sufficient area to place the sound absorption material or configuration, whereas the side walls offer insufficient areas for sound absorption treatment. Therefore, in the redesign scheme, priority should be given to ceiling sound absorption treatment, followed by the treatment on the side walls appropriately.

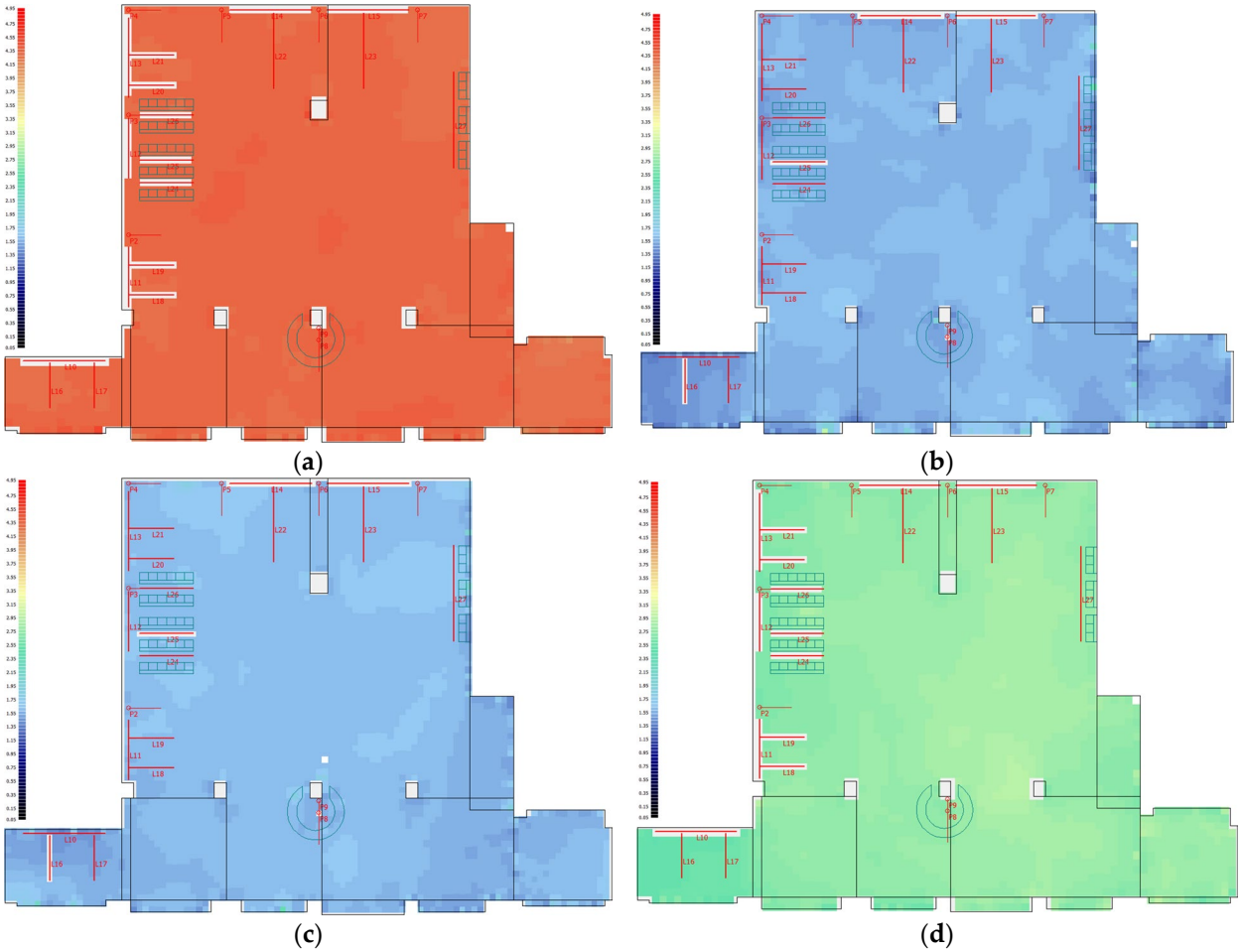


Figure 11. T_{30} of different schemes: (**a**) original scheme; (**b**) Scheme 1; (**c**) Scheme 2; (**d**) Scheme 3.

3.2.3. The Hall's Floor Height

The field survey indicates that most outpatient halls in Nanning feature single-story ceilings ranging from 2.8 m to 4 m in floor height. Some halls are equipped with air conditioning ducts, cable trays, and ventilation ducts in the equipment layer between the ceiling and floor. Some hospitals feature a corridor-style atrium that runs through several floors, which makes halls much higher than 4.0 m. Since floor height determines the volume of the hall directly, and volume is closely related to reverberation time and building function, the floor height affects the acoustic environment quality in a hall. Under the condition of a confirmed floor plan, the volume of the hall varies with its floor height. Therefore, this study will quantitatively analyze the influence of the outpatient hall volume variation on various acoustic parameters. Based on the design of the hall with a height of two floors, five schemes with different floor heights, which vary in 0.2 m as a change step, are listed in Table 8. The simulation results of these schemes are presented in Figure 12.

Table 8. Schemes with different floor heights.

Scheme	Height	Volume
1 (Original)	6.8 m (Original)	4823.8 m^3
2	6.6 m	4676.3 m^3
3	6.4 m	4528.8 m^3
4	6.2 m	4381.3 m^3
5	6.0 m	4233.8 m^3

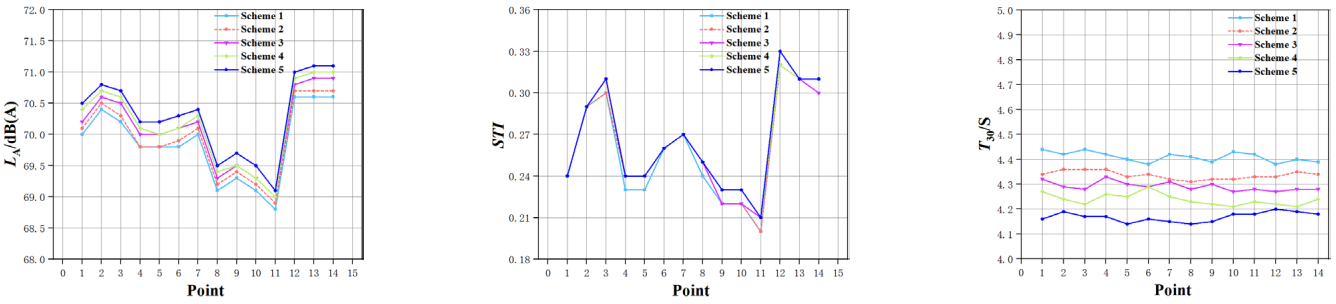


Figure 12. Comparison of results for different floor height schemes: (**a**) L_A; (**b**) *STI*; (**c**) T_{30} at 500–1000 Hz.

As shown in Figure 12a, specifically, as the floor height is reduced by 0.8 m, L_A increases by only 0.5 dB. In Figure 12b, when the average *STI* increases from 0.26 in Scheme 1 to 0.27 in Scheme 5, its total increases are only 0.01. However, the *STI* at receiving points R_1, R_2, R_6, R_7, and R_{13} remains unchanged. These points cover pharmacy, registration, and random areas. Therefore, *STI* in these areas can reflect the speech intelligibility of patients during communication. It indicates that the adjustment of the hall's height has a tiny effect on *STI*. Simultaneously, the floor height has a similar effect on T_{30}. Figure 12c illustrates that the T_{30} decreases from 4.41 s in Scheme 1 to 4.17 s in Scheme 4 as the floor height of a hall reduces from 6.8 m to 6.0 m. As the cumulative height reduction in the hall reaches 0.8 m, the reduction in T_{30} is only 0.24 s.

The analysis indicates that the effect of adjustment of the hall's floor height (or volume) to improve the acoustic environment quality is marginal. The variation in the floor height does improve T_{30} and *STI* to a small extent, but it also causes a slight increase in L_A. Among the three parameters L_A, *STI* and T_{30}, T_{30} is most sensitive to variation in floor height. Excessive floor height increases the spatial volume and potentially gives rise to prolong reverberation time and echoes. Conversely, the lower floor height makes people feel oppressive in the hall, and the psychological stress on patients occurs. In order to balance function with acoustic performance, the floor height should ideally range between 3.0 m and 3.4 m in a single-story hall. For the most commonly used double-story halls, the floor height should be maintained between 6 m and 6.8 m.

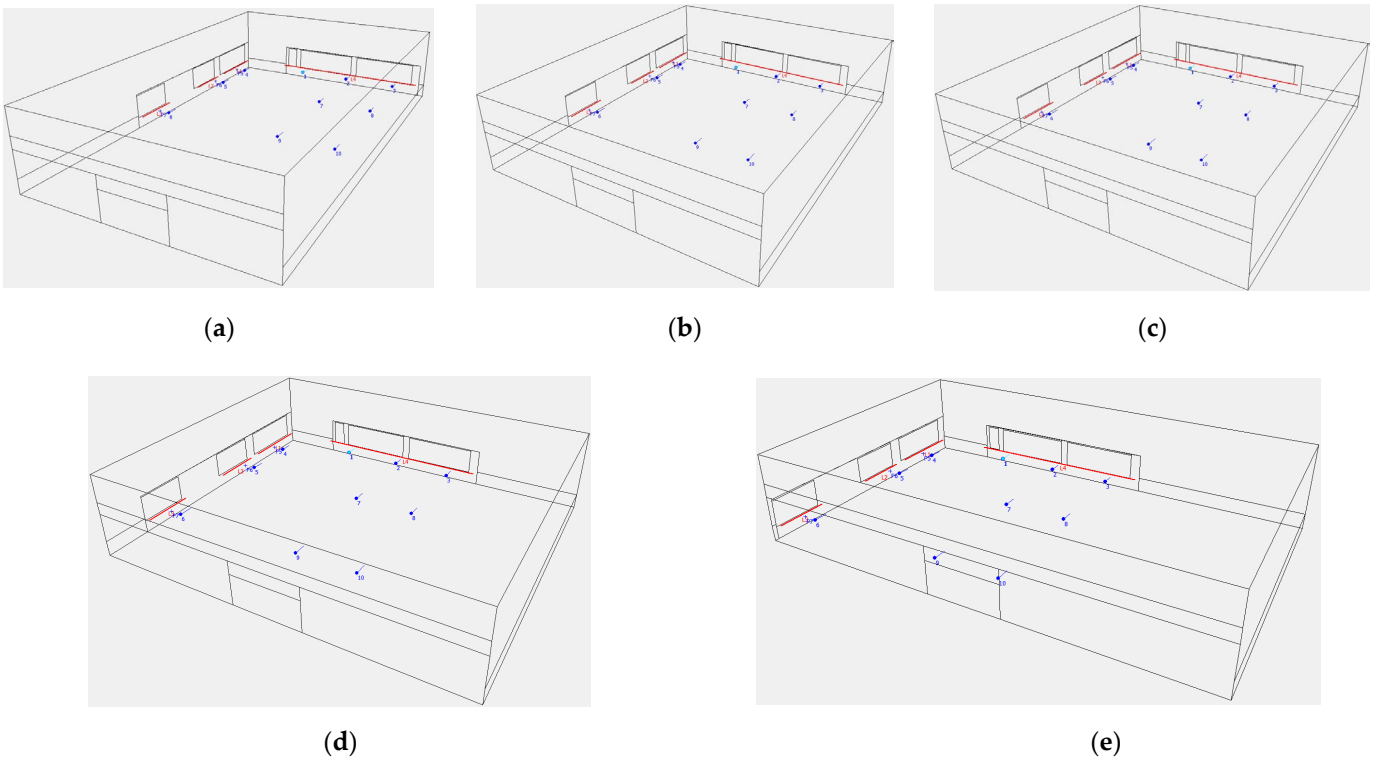
3.2.4. The Planar Length-to-Width Ratio

Since the rectangular floor plan has directional guidance for the patients, most outpatient halls, as usual, adopt this kind of floor plan. When the area of a rectangular floor plane remains constant, its length-to-width ratio influences the functional zoning and traffic streamline within the indoor space and in turn affects the distribution of noise sources. Therefore, based on actual survey findings, five planar length-to-width ratio schemes were proposed as shown in Table 9, and a simulation model depicted in Figure 13 was established to analyze how different ratios impact the acoustic environment.

The plan of the original scheme is not a regular rectangle. It is necessary to simplify the original plan into a rectangle shape. In Scheme 3, based on the original area of 695.57 m^2 and a length-to-width ratio of about 1.08:1, a rectangle measuring approximately 27.4 m in length and 25.4 m in width was derived through calculation. The length and width of the other schemes were all adjusted based on those of Scheme 3. For the sake of analysis, every simulation model has 10 similar receiving points, including three points in the registration area (R_1, R_2, R_3), three points in the pharmacy area (R_4, R_5, R_6), and four points in the random area (R_7, R_8, R_9, R_{10}).

Table 9. Schemes with different planar length-to-width ratio.

Scheme	Length	Width	Ratio of Length to Width	Plane Area
1	33.5 m	20.7 m	1.618: 1	693.45 m^2
2	28.9 m	24.1 m	1.2: 1	696.49 m^2
3 (Original)	27.4 m	25.4 m	1.08: 1	695.57 m^2
4	24.1 m	28.9 m	0.83: 1	696.49 m^2
5	20.7 m	33.5 m	0.618: 1	693.45 m^2

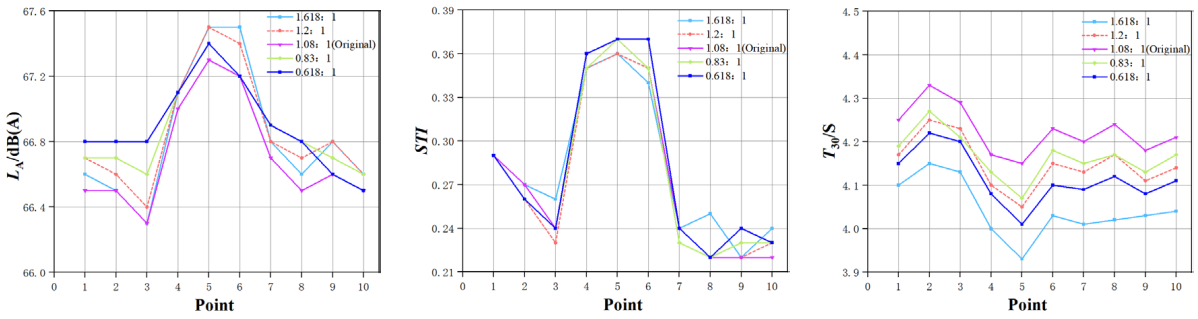


(**a**) (**b**) (**c**)

(**d**) (**e**)

Figure 13. Schemes with different planar length-to-width ratio: (**a**) 1.618:1; (**b**) 1.2:1; (**c**) 1.08:1; (**d**) 0.83:1; (**e**) 0.618:1.

Simulation results of different planar length-to-width ratios are shown in Figure 14. When the planar ratio decreases from 1.618:1 to 0.618:1, as shown in Figure 14a, the variation in noise level at each receiving point is within 0.5 dB, which indicates that the planar length-to-width ratio has minimal effect on indoor noise level.



(**a**) (**b**) (**c**)

Figure 14. Acoustic parameters of schemes with different planar length-to-width ratio: (**a**) L_A; (**b**) *STI*; (**c**) T_{30} at 500–1000 Hz.

Figure 14b shows the *STI* variations corresponding to different planar length-to-width ratios in the hall. As the ratio decreases from 1.618:1 to 0.618:1, the *STI* at R_2 and R_3 decreases by 0.01 and 0.02, while the *STI* at R_4, R_5, R_6 increases by 0.01, 0.01, and 0.03, respectively. As the ratio decreases, the distance between the receiving points R_2 and R_3 and the side walls increases, which results in greater attenuation of reflected sound energy. Although the distance between points R_2, R_3 and the rear wall decreases, reflections from the rear wall are strengthened. Therefore, the windows of pharmacy and registration can be placed along the two parallel short sides of the rectangular hall, which can not only increase the proportion of early reflections from the side walls and improve speech intelligibility in the main patient gathering area but also increase the distance between east and west windows to reduce noise interference.

In Figure 14c, as the ratio decreases from 1.618:1 to 0.618:1, it illustrates that the T_{30} first increases gradually, reaches its maximum at the ratio of 1.08:1, and then decreases. The average T_{30} of the five schemes ranges between 4.04 s and 4.23 s; specifically, the T_{30} is 4.23 s when the ratio is 1.08:1. At the golden ratio of 1.618:1, T_{30} decreases to its minimal value of 4.04 s. The closer the plane is to a square, the longer the reverberation time. Although the planar length-to-width ratio has a tiny effect on reverberation time, the floor plan of the outpatient hall should avoid being designed as a square one.

4. Redesign of the Outpatient Hall

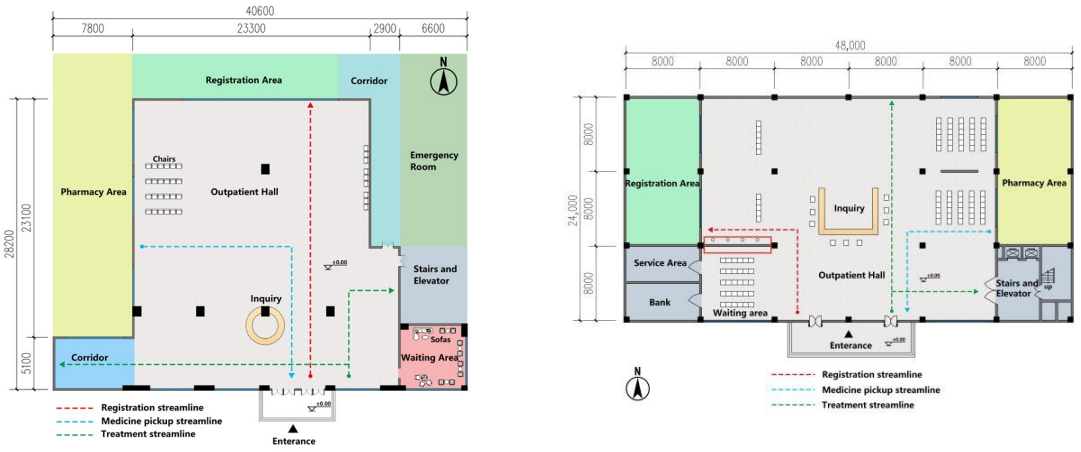
Based on the simulation analysis, a redesign strategy can be proposed, i.e., the acoustic environment quality of the outpatient hall should be improved by form redesign and sound absorption schemes.

4.1. Form Redesign

The form redesign includes two steps, namely planar redesign and section redesign. Planar redesign needs to give priority to efficient traffic streamline and appropriate functional zoning to solve issues like traffic streamline intersection and discrete noise sources within certain areas. Section redesign, meanwhile, determines the floor height of each zone according to its specific function, thereby controlling the overall volume of the hall, which influences the reverberation time.

4.1.1. Planar Redesign

Figure 15a shows the horizontal traffic streamlines in the original plan, where red, blue, and green dashed lines represent patient registration, medication pickup, and treatment streamline, respectively. Analysis of these streamlines reveals that the registration area is too far from the main entrance. The registration streamline (red dashed line) spans approximately 28 m directly through the outpatient hall in a north–south direction and intersects with the treatment streamline (green dashed line), which causes crowd congestion. The pharmacy area is also placed inconveniently far away, so the medicine pickup streamline (blue dashed line) is about 26 m, while the treatment streamline from the pharmacy to the vertical traffic core (elevators) on the right side extends approximately 30 m. This layout prolongs patient stay duration, hinders efficient crowd dispersal, and easily leads to congestion. Additionally, functional area lacks clear separation—for instance, the pharmacy adjoins the registration area, which causes the superposition of the loudspeaker sound from the pharmacy, speech from the registration, and activity noise, which is prone to produce the Lombard effect. Therefore, the placement of the pharmacy and the registration should be adjusted in the redesign scheme.



(**a**) (**b**)

Figure 15. Plans before and after redesign: (**a**) original plan and traffic streamline; (**b**) redesign plan and traffic streamline.

In terms of aforementioned issues and the proposed design strategies, a redesigned plan scheme is presented in Figure 15b. The floor plan of the hall retains a rectangular shape as the original one does, and the planar length-to-width ratio close to the golden ratio is adopted to reduce reverberation time as much as possible. Meanwhile, the registration and inquiry areas are arranged close to the main entrance. The registration streamline is shortened from the original 28 m to 12 m, which improves accessibility to each zone. The registration and waiting area are separated by a wall, which is in the red-framed area in Figure 15b, to abate noise disturbance from the registration area. Vertical traffic cores (stairs and lifts) are arranged on the right side of the hall adjacent to the main entrance. If patients go upstairs for medical treatment, the distance of treatment streamline can be shortened from 12 m to 8 m. As the final step in the patient journey, the pharmacy and medication pickup area are placed on the right side of the hall near the exit and elevators, which can shorten the medicine pickup streamline from 26 m to 14 m, facilitate efficient patient dispersal, and reduce lingering time. This planar redesign ensures a distance of above 16 m between the registration and the pharmacy, which achieves reasonable functional zoning and disperses concentrated noise sources. Thus, the Lombard effect is effectively mitigated.

4.1.2. Section Redesign

Figure 16a is a simplified cross-section of the original outpatient hall, where main functional areas such as inquiry, registration, pharmacy, and waiting area are located. Therefore, the section redesign can follow the scheme as shown in Figure 16b. The hall's volume is reduced by the reduction in the floor height of the main function area, and then, the sound absorption structure is placed on the ceiling and side wall near these areas to abate the acoustic defects, such as high noise level and long reverberation time. In this section, the specific redesign scheme is presented in Figure 16c: the main functional areas are reduced from two stories to one, with a floor height of 3.4 m. To achieve optimal daylighting, the original double-story design at the entrance is unchanged, with a height of 6.8 m. The consultation rooms and waiting rooms on the second floor are separated from the hall by walls, which can prevent noise interference from the upper floor. To improve the hall's acoustic environment quality, the redesigned section preserves the open feeling at the main entrance to achieve a balance between architectural form and functional performance.

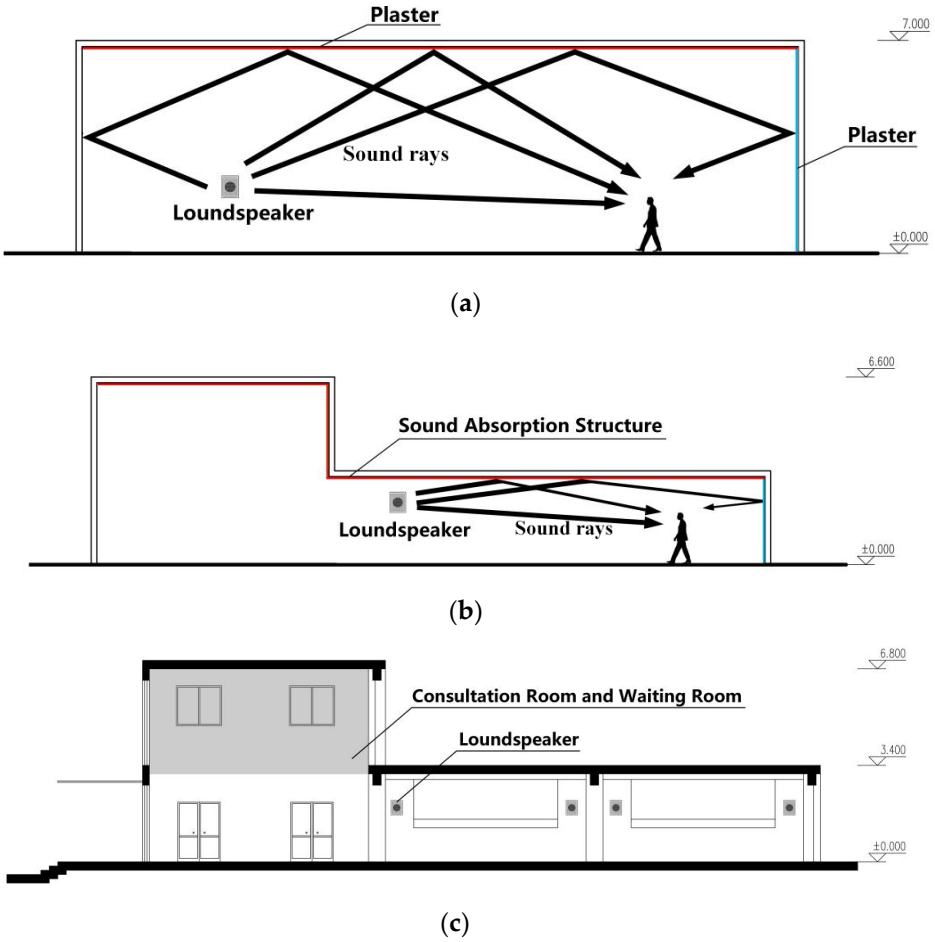


Figure 16. Section redesign: (**a**) original section; (**b**) redesigned section; (**c**) detailed redesigned section.

4.2. Sound Absorption Design Scheme

For the sound absorption design, a patch sound absorption scheme is preferred to a uniform one. Priority is given to areas with higher occupant density, where people are more congested. Sound absorption is applied to the surrounding ceilings and side walls. The ceiling offers substantial area for absorption and can be treated with 16 mm thick K-13 sound absorption coating material. The side walls adopt perforated gypsum plates, which effectively attenuates sound reflection and flutter echoes between the parallel walls. Although the floor area is comparable to the ceiling area, it is not suitable for placing the sound absorption materials in the humid and hot regions. Thus, the floor is still tiled. The sound absorption coefficients of these sound absorption structures in the redesign scheme are listed in Table 10 [35].

Table 10. Sound absorption coefficients of interior surface in the hall.

Name of Material	Frequency/Hz					
	125	**250**	**500**	**1000**	**2000**	**4000**
Perforated gypsum plates	0.27	0.51	0.28	0.34	0.28	0.32
Aluminum plate	0.01	0.01	0.01	0.02	0.02	0.02
Metal seats (occupied)	0.16	0.2	0.31	0.38	0.46	0.4
16 mm thick K-13 sound absorption coating	0.05	0.16	0.44	0.79	0.9	0.91

5. Discussion

In order to evaluate the redesign scheme, a simulation model of an outpatient hall, as shown in Figure 17, was established. Then, the analysis of the redesign scheme was conducted by Odeon software. The comparison of acoustic parameters in the original and redesigned schemes shown in Table 11 illustrates that the noise level L_A decreases from 69.3 dB to 65.0 dB. However, it is still 10 dB above the standard limit of 55 dB. This indicates that meeting the standard requirements of 55 dB requires more than just absorption and form design. Active noise management should be conducted in the outpatient hall due to high occupancy, hard-surfaced spaces and unevenly distributed sound sources. For instance, prominent signage can be displayed on the wall to remind patients and their families to maintain a quiet environment, avoid loud conversations and set mobile phones to silent mode or use headphones. In the pharmacy area, electronic display screens can be utilized to notify patients of medication pick-up via text, which can replace conventional public announcement. Additionally, sound masking systems can be introduced in the hall. By playing low-frequency and soothing background sounds like ocean waves or natural wind in the waiting area, this can reduce the perception of noise. Therefore, the reduction of 4.3 dB is considered substantial and acceptable given constraints such as high occupant density, inherently noisy acoustic environment and practical difficulties in applying sound absorption treatments to all interior surfaces. The average *STI* improves from 0.14 to 0.46 and meets the audible requirement, i.e., $STI \geq 0.45$. In the redesigned scheme, the average reverberation time T_{30} at middle frequencies decreases from 4.66 s to 1.17 s and meets the national standard requirements. The comparative analysis indicates that the acoustic environmental quality in the redesigned scheme is improved significantly, and the proposed measures to enhance the outpatient hall's acoustic environment are feasible.

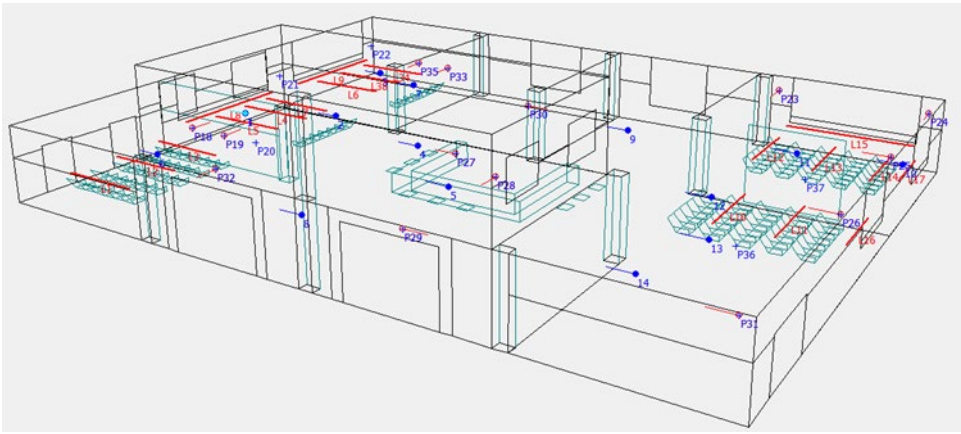


Figure 17. Simulation model of the redesigned scheme.

Table 11. Comparison between the original and the redesigned scheme.

Acoustic Parameters	Frequency/Hz					
	125	**250**	**500**	**1000**	**2000**	**4000**
T_{30} (Original scheme)	5.84	4.3	4.62	4.69	4.61	3.54
T_{30} (Redesigned scheme)	2.21	1.7	1.34	0.99	0.92	0.87
STI (Original scheme)	0.14					
STI (Redesigned scheme)	0.46					
L_A (Original scheme)	69.3 dB					
L_A (Redesigned scheme)	65.0 dB					

Therefore, form redesign of the outpatient hall can be carried out from two aspects: planar redesign and section redesign. The floor plan of the hall should be designed as a

rectangular one rather than a square one. When the planar length-to-width ratio of the rectangle is close to the golden ratio, the reverberation time is minimized. Simultaneously, the registration and pharmacy areas should be placed along the short side of the rectangle. Through appropriate functional zoning and optimized traffic streamline, the dispersion of noise sources and the mitigation of Lombard effect are achieved. Section redesign should determine appropriate floor heights based on the specific requirements of each functional area. Simulation analysis indicates that modification of floor height has limited impact on acoustic quality improvement. Therefore, the overall hall height should be controlled within a range that satisfies architectural requirements. The registration, pharmacy and waiting areas should not have the same floor height as the atrium. Instead, their floor heights should correspond to their actual functional needs.

Given the interior surface characteristic in an outpatient hall, patch sound absorption is employed instead of uniform sound absorption arrangements. Appropriate sound absorption configurations can be placed on the side walls and ceilings near crowded places such as registration and medicine pickup areas. Simulation analysis indicates that this kind of sound absorption scheme significantly reduces noise level and reverberation time and enhances speech intelligibility.

In the case of the floor height, the simulated *STI* ranged from 0.27 to 0.28, which shows an evident difference from the measured *STI* of about 0.14. This is due to the complexity of the actual measurement environment and a somewhat simplified simulation model. Additionally, the indoor impulse responses were obtained in an unoccupied condition, while the simulation assumed at least 1/3 occupancy in the outpatient hall. Nevertheless, both measured and simulated *STI* are all below 0.3, which indicates the low speech intelligibility in this outpatient hall. Acoustic design is often conducted in the worst conditions, i.e., the unoccupied condition corresponding to the measurement. Once the acoustic indicators meet the code requirements under unoccupied conditions, they are more likely to be satisfied in actual occupied conditions. Therefore, during the redesign phase, we also used measured *STI* rather than simulated *STI* to verify the proposed redesign strategies.

Although this study focuses on a specific case of a hospital outpatient hall, the issues of noise, speech intelligibility and reverberation time it addresses are equally prevalent in the high occupant density of various types of public buildings' hall, such as libraries, museums, shopping malls, railway stations and airport terminals. Therefore, it is necessary to conduct an acoustic redesign study for the outpatient hall. The redesign strategies and optimization methods of the acoustic environment proposed from this study hold significant reference and application value for resolving common acoustic challenges in such public spaces.

For spatial configuration, public buildings inevitably house functional areas where generate high noise levels. In such areas, an excessively high design of floor height has no substantial benefit to functional use but rather significantly increases reverberation time due to the large volume. Meanwhile, noise in these areas can be easily diffused into quiet areas because of an opening design. Therefore, it is essential for optimizing the acoustic environment to implement differentiated floor height strategies during the schematic design phase.

Functional zoning is closely related to streamline design. Unreasonable functional zoning leads to acoustic interference between different areas. For instance, in a hospital outpatient hall, the noisy consultation area typically disrupts the waiting area. Unreasonable streamline design, on the other hand, may result in streamline intersection and long paths, which cause crowd congestion and the Lombard effect, as well as prolong stay time and the duration of noise exposure. Therefore, optimized functional zoning should be prioritized to shorten streamline paths and enhance efficiency. Specific strategies include clustering

areas with similar or closely related functions and maintaining adequate distances between dynamic areas (e.g., consultation areas) and static areas (e.g., waiting areas) to achieve effective acoustic separation.

However, architectural design is a complex systems engineering. Adjusting its length-to-width ratio and floor height is far from being as simple and continuous as inputting numerical values. It often requires only minor and discrete adjustments. In actual projects, form design is also constrained by building structures and modular construction. Therefore, the number of schemes with different floor heights and length-to-width ratios proposed in this study are limited.

From an acoustic perspective, minor adjustments of form do not alter the volume of the hall significantly. Most early reflections still come from a few specific directions (such as side walls, ceilings, and floors). Therefore, such adjustments have a limited impact on *STI* and L_A. In comparison, flutter echo and late decay may be better controlled by the targeted-patch absorption.

6. Conclusions

Generally, the poor acoustic environment quality in a hospital outpatient hall is due to inadequate architectural acoustic design. In the hall, people often feel stress from vociferous environment and language communication difficulties, which evidently impair the patient's visit experience and negatively impact their recovery. Therefore, based on field survey and in-situ acoustic measurements, the analysis of the current acoustic situation in an outpatient hall of a hospital in South China was carried out. It reveals that the acoustic parameters in the hall, such as noise level, speech intelligibility and reverberation time, do not meet the requirements of the national code or standard. Consequently, it is necessary to improve hall's acoustic environment quality through redesign.

With respect to the acoustic environment in the outpatient halls, some improvement measures, such as sound absorption treatment, adjustment of the hall's floor height and optimization of length-to-width ratio, are proposed. Additionally, corresponding redesign strategies are developed by further research. The redesign strategies proposed in this study offer novel insight into the redesign of the outpatient hall in a hospital. The findings provide theoretical and technical support for the acoustic design in healthcare facilities and have practical guidance for enhancing the acoustic environment quality within a hospital public space.

Given the practical constraints of modular construction and the fixed structures and plans of built buildings, the proposed acoustic optimization strategies are mainly targeted at the scheme design phase. The conclusion about golden ratio is primarily applicable to hospital buildings with approximately rectangular plans. The applicability of floor height design is also somewhat limited. However, the research findings clearly indicate that sound absorption design plays a more significant role than form design (planar design and section design) in acoustic environment optimization. Subsequent studies will focus on more efficient functional zoning and streamline design to enhance the acoustic performance of such spaces.

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Abbreviations

The following abbreviations are used in this manuscript:

NRC	Noise Reduction Coefficient
STI	Speech Transmission Index
MTF	Modulation Transfer Function
MTI	Modulation Transfer Index
SNR	Signal-to-Noise Ratio

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