The effectiveness of acoustic treatments in general hospital wards in China

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Abstract

The aim of this study was to quantitatively determine the effect of various acoustic treatments in hospital wards on reverberation time, noise levels and users' subjective evaluation during normal operations by installing a sound absorptive ceiling and soundproof door and windows. Patient rooms, corridors and nurse stations in two general wards in a Chinese hospital were chosen as the study sites. The quantitative measurements showed that the reverberation time of 500 Hz–1 kHz decreased by 13~53% to approximately 0.3 s in the patient rooms, corridors and nurse stations after the acoustic treatment. Noise levels in the corridors and nurse stations decreased significantly by 5~11 dB(A) (p<0.01). Smaller differences were found in the patient rooms with noise levels decreasing after application of the acoustic treatment by 2~4 dB(A) (p<0.01) during the daytime and 5~6 dB(A) (p<0.01) during the nighttime. Questionnaires indicated that acoustic treatment could significantly decrease the negative impacts of noise on patients' conversations (p<0.01) and emotional state (p<0.01) and extend the quiet period during the night-time for sleep. Meanwhile, staff members reported that they could take advantage of speaking with a lower voice and having a higher working efficiency at the nurse station after changing the ceiling material to an absorptive one.

Keywords: hospital ward; sound environment; acoustic treatment; noise control; patient; medical staff

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1. INTRODUCTION

The prevention of noise exposure is important for both citizens and workers in order to avoid high noise levels that will cause complaints [1, 2] and health effects such as sleep disorders with awakenings [3], learning disabilities [4], hypertension and ischemic heart disease [5-9], reduced working performance [10, 11], and annoyance [12, 13]. Especially for patients, noise levels and acoustic comfort are key parameters to be considered, as patients are more vulnerable to noise disruption, compared with healthy people [14-18]. This may result in delayed wound healing and lead to mental diseases in severe cases [19, 20]. Besides, excessive noise tends to cause stress and impaired communication, and these in turn, are likely to influence short-term memory, quickly tire staff and result in an increased number of medical errors [16, 21].

To minimize the negative effects of noise on patients and staff, the World Health Organization (WHO) suggested that the noise level should not exceed 30 dB(A) in therapy rooms and other hospital areas [14]. Similar limitations on the noise level of hospital wards have been published in related guidance and standards in several countries [22]. China also has standards restricting the noise level in sensitive areas of hospitals; the level of background noise in patient rooms has been limited to 40 dB(A) during the daytime and 35 dB(A) during the nighttime [23, 24]. However, according to a large number of studies, the noise level in hospital wards in various countries cannot be reduced to the recommended value from the WHO or the corresponding national standards. A review of studies from widely differing types of medical units and from hospitals located in different countries reported that noise levels in hospitals around the world have increased steadily by 0.4 dB(A) per year since 1960, with ambient noise levels exceeding the WHO's recommendation by 15~20 dB(A) in 2005 [25].

For many years, most relevant studies have focused on areas that are perceived to be particularly noisy, such as intensive care units (ICUs) and operation rooms (ORs). In most ICU wards, noise is generated mainly by heavy-load medical equipment from internal wards with equivalent noise levels of approximately 55~65 dB(A) [17, 25-33]. There has been a general assumption for many years that general wards are quieter than ICU wards due to fewer pieces of medical equipment operating in the room. Thus, the noise level issues in general wards has been largely ignored by previous studies.

In recent years, increasing attention has been given to the acoustic condition in general wards. One study from a tertiary care hospital in the United States indicated that noise levels from three general wards were higher than those from the ICU by 6~10 dB(A) based on short-term measurements (2 hr) during the daytime [34]. Another study conducted in an National Health Service (NHS) community hospital in the UK further indicated that the movement of patients in beds correlates with noise levels above 68 dB during the day and above 60 dB at night [35]. Our previous study conducted in a Chinese hospital indicated that the primary noise sources in general wards were distinctly different from those in ICU wards [36]. Although medical equipment was not a significant noise source and had only a slight contribution to the noise level of general wards, a higher noise level was found in general wards than in the ICU as a result of the crowded hospital environment. Within their rooms, the sleep quality of patients was affected by noise not only from the internal wards but also from the corridor and outside due to the poor soundproofing quality [36]. Meanwhile, the working efficiency of nurses and doctors at adjacent nursing stations might also be affected [36].

To provide a quiet environment to promote rest, healing and well-being for patients, several noise-reduction interventions, including behavioral modifications such as earplug use and staff education, have been proposed by most studies on this topic. Wearing earplugs, a simple noise-reduction intervention, can reduce the patient's perception of ambient noise and improve their sleep quality [37-40]. However, it also blocks their perception of spoken information. Therefore, wearing earplugs is more suitable for critical patients in the ICU ward who cannot move or speak. Meanwhile, evidence from several studies highlights that changing staff behavior through noise awareness and education programs can significantly reduce peak noise levels and decrease the perception of bothersome noise [41-43].

However, acoustic treatments such as acoustical ceiling tiles may be more useful in permanently reducing sound levels and increasing speech intelligibility in the hospital setting [44-46]. Yet, very few studies have investigated the use of partial acoustic treatments in operating hospitals to ensure the safety of patients and the working efficiency of medical staff. MacLeod et al. [44] indicated that replacement of ceiling tiles and installation of absorbing wall panels reduced the noise level in ward areas by 4~6 dB(A). Farrehi et al. [45] also found that the acoustic panels primarily affected the decay or diffusion of mid-frequency and high-frequency sound levels, showing a decrease in the noise level in an intervention ward of 3.4 dB(A). Furthermore, S.K. Lau [46] found that the installation of an absorptive ceiling and carpet in hospital corridors could improve the satisfaction of both patients and staff. Blomkvist et al. [47] indicated that changing the ceiling tiles to tiles with sound absorptive properties in the CCU ward could improve reverberation times and speech intelligibility, which can decrease pressure and strain among staff groups.

However, previous studies have mainly considered the impact of sound-absorbing treatment on the acoustic environment of patient rooms and public areas. Few research efforts have been made to investigate the effects of enhancing the sound insulation between patient rooms and the outside environment, which should be considered in general wards. Meanwhile, there is a lack of appropriately designed studies to test the effectiveness of interventions on noise level reduction and to evaluate the perception of patients and staff in general wards.

Therefore, the aims of this comparative study are to (1) systematically evaluate the effectiveness of acoustic treatments on objective measures of the acoustic conditions in hospital wards, including reverberation time, equivalent noise levels, impulsive peak noise level and background noise level during daytime and nighttime as well as noise level variation and spectrum over 24 hours; (2) explore the impact of changes in noise on the conversation, emotional state, sleep and working efficiency of patients and staff; (3) discuss the influences of objective acoustic conditions on behavior and (4) make acoustic recommendations.

A series of interventions, including the use of sound absorptive and sound insulating materials, were conducted in patient rooms, corridors and nurse stations to reduce the internal noise level of two typical general wards in a tertiary hospital in China. Data on the objective acoustic condition and participants' subjective experience were collected before and after the renovation with a series of acoustic measurements and a questionnaire, respectively.

2. METHODOLOGIES

2.1 Case study sites

As a tertiary hospital in southwest China, Yibin 2nd People's Hospital is very large, with a bed capacity exceeding 3000, provides the highest level of service, medical technology and research, medical equipment, care providers, management and medical quality and serves as a medical hub providing care to the residents of the local region in Sichuan Province. Medical staff and patients from the cardiology and oncology departments have higher requirements for optimization of the acoustic environment, and limited acoustic treatments are allowed by hospital management. The ward information for these two departments is shown in Table 1.

The cardiology ward (CA) is on the 3rd floor of the main 'L-shaped' inpatient building. The building was originally built in the 1980s and renovated in the 2000s. In total, 85 beds are in the ward, along with 32 other temporary beds arranged in the corridor to address extra inpatients. A nurse station is located at a central location in the corridor. One wing of the CA containing the nurse station, as shown in Fig. 1, was chosen as the first case study site. The walls and floors in patient rooms and public areas were hard surfaces, and the suspended ceilings in the corridor and nurse station were tiled in 10 mm mineral fiber tile with a Noise Reduction Coefficient (NRC) of 0.35 as measured by an impedance tube.

The oncology ward (ON) is located in a relatively new inpatient building that was completed in 2003. The 5th floor of this ward, including a total of 25 beds in ten 2-bed rooms and one 5-bed room, was chosen as the second case study site. Although more aesthetically pleasing decorations are found in the ON compared with that CA, acoustic conditions were ignored in the interior decoration efforts. All the walls and floors in the ward had hard surfaces, without any sound absorbing materials applied. The sliding windows and thin wooden door in each room also led to poor sound insulation from the corridor and outside environment.

Table 1. Original state of the cardiology and oncology department wards

		Area (m^2)	Height (m)	Ceiling	Floor	Door	Windows	Measured parameters	
								T_{30}	SPL
Nurse station	CA	37.5	2.7	Mineral wool	Terrazzo	N/A	N/A	✓	✓
	ON	38.7	2.3	Plaster	PVC			✓	✓
Corridor	CA	49.2	2.6	Mineral wool	Terrazzo			✓	✓
	ON	53.8	2.5	Plaster	PVC			✓	✓
5-bed room	CA	29	3.2	Concrete	Terrazzo	Solid wood	Single glazed	✓	N/A
	ON	35	2.5	Plaster	PVC	Hollow wood	Double glazed	✓	N/A
2-bed room	CA	11.9	3.2	Concrete	Terrazzo	Solid wood	Single glazed	✓	✓
	ON	16.2	2.5	Plaster	PVC	Hollow wood	Double glazed	✓	✓

2.2 Acoustic treatments

To reduce reflected sound energy from indoor noise sources inside the rooms, Armstrong Bioguard 19 mm antibacterial mineral fiber tiles with high sound absorption (NRC 0.75) were applied as the new ceiling in the nurse stations, corridors, and patient rooms of the two wards. Meanwhile, the original thin wooden doors between the patient room and corridor were replaced by soundproof doors with an automatic bottom seal and $R_w+C=37$ dB. Additionally, the windows in the patient rooms were replaced with soundproof windows with $R_w+C_{tr}=28$ dB. To minimize the visual differences, the size and color of the new doors and windows were consistent with the original ones (see Fig. 1). After discussion with the management and medical staff, acoustic treatment areas were limited to the nurse station, corridor, one 5-bed patient room and one 2-bed patient room in each ward to ensure nursing activities and patient safety.

Fig. 1. Floor plans and renovation process of acoustic treatment areas

2.3 Measurement procedures

To test the intervention effectiveness of the acoustic treatment on the sound field in each area of the wards, the reverberation time (RT) and long-term continuous noise level measurements were conducted at the same location before and after the renovation, as shown in Fig. 1.

To ensure a relatively low ambient noise level and minimize the noise impact on patients' sleep during the RT test, it was decided after consultation with the medical staff to conduct RT measurements between 21:30 and 22:30 on weekends. All the doors and windows of the wards were kept shut during the RT tests. A Bruel and Kjaer 2250 sound level meter and an omni-directional loudspeaker were chosen to test T_{30} in multiple locations, as shown in Fig. 2a. At least three receiver positions were placed for the corridor and nurse station, and two receiver points were placed for the patient rooms according to ISO 18233:2006 [48].

To measure the noise level simultaneously in the corridor, the nurse station and a patient room, three precision Type 1 sound level meters (Aihua AWA6228-3) were used to record the A-weighted SPL and 1/3 octave spectrum over the same period. To minimize the potential interference with general healthcare activities, two meters was suspended on the ceiling of corridors and nurse stations, as shown in Fig. 2b. The third meter was fixed to the infusion stand near the bed in the patient room, as shown in Fig. 2c. As noise levels can vary significantly a during 24-hour period, the meters were set to continuously record the sound level every second for three consecutive working days in each location to guarantee an accurate representation of the typical acoustic environment. Meanwhile, the background noise levels in two patient rooms in the CA were also measured while the rooms were unoccupied for 24 hours. The recorded data were analyzed to calculate the averaged L_{eq}, L_{10} (impulsive peak noise level) and L_{90} (background noise level), number of noise events with L_{eq_1min} over 70 dB(A) (such as a trolley moving, loud speaking, shouting, or a phone ringing, which can have negative effects on spoken conversation and short-term memory and elicit a startle response and annoyance), SPL variation and frequency spectra.

(a) (b) (c)

Fig. 2 Objective measurements: (a) RT test at the nurse station, (b) SPL measurement at the nurse station, (c) SPL measurement in the patient room

2.4 Questionnaire survey

To compare the patients and medical staff members' perception of the acoustic conditions, the questionnaires were administered in the CA before and after the renovation with permission from the hospital. Participants were asked to subjectively evaluate several aspects of the acoustic environment, such as 'main noise sources' and 'the impacts of noise'. Most of the questions were designed on a standard 5-point scale for the convenience of data analysis.

In total, 200 questionnaires were distributed to patients and staff in the study area in the CA, and 168 validly completed questionnaires were collected, representing a response rate of 84.0%. Responders included 45 patients (22 patients in the corridor and 23 in patient rooms) and 39 medical staff members (31 nurses and 8 doctors) before the renovation and 43 patients (19 patients in the corridor and 24 in patient rooms) and 41 medical staff members (33 nurses and 8 doctors), after the renovation.

2.5 Statistical analysis

The statistical software SPSS 18.0 was used to test the significance of differences in sound pressure levels before and after the renovation. A paired-sample t test was used to compare the L_{eq}, L_{10} and L_{90} values. Nonparametric tests (Kruskal–Wallis ANOVA) were adopted to test the differences in the staff members and patients' perception of the acoustic environment before and after the treatment. The significance level was set at 5% (p=0.05) for all tests, with * representing $p < 0.05$ and ** representing $p < 0.01$.

3. RESULTS

3.1 Effect on the reverberation time

As shown in Fig. 3, a shorter RT was found at each location across the two departments after the change in ceiling tiles, particularly for the medium and high frequencies (500 Hz–4 kHz), which is related to the sound absorbing ceiling tile having an absorption coefficient above 0.5 for frequencies higher than 250 Hz.

By comparing the nurse stations of the two departments, it is worth noting that there was an apparently higher RT at medium frequencies (500 Hz–1 kHz) in the ON before renovation, despite the size of the two nurse stations being similar. The reasons for this difference were that there was a sound reflection off the ceiling in the ON nurse station and the space is relatively enclosed (as shown in Fig. 1), resulting in a longer time needed for the reflected sound energy to decay. However, the nurse station in the ON showed the most significant decrease in RT after the change in ceiling tiles. The RT of the ON nurse station dropped by 53.4% from 0.58 to 0.27 s at medium frequency; the same RT, 0.27 s at medium frequency, was measured in the nurse station in the CA after the change in ceiling tiles. This is largely because the nurse station in the ON has the largest ratio of ceiling area to other surface areas, and therefore could show the largest change in sound absorption of the room.

A similar difference was found in the corridors between the two departments. The CA corridor had significantly lower RTs at medium and high frequencies (500 Hz–4 kHz) before the change in ceiling tiles. This was largely due to the sound absorption characteristics of the temporary beds that were in the CA corridor. As a result, there were insignificant changes in the RT values in the CA corridor after the change in ceiling tiles, with 13.6%, 13.4% and 26.0% declines at low, medium and high frequencies, respectively, compared with 25.4%, 42.5% and 41.1% declines measured in the ON corridor.

Although there are no reverberation time requirements for patient rooms in China, the WHO's guidelines [14] and the Danish Building Regulation (BR18) [49] indicate that the reverberation time in a patient's room, as a rehabilitation place with communication needs, should not exceed 0.6 s in the range of 125 Hz–4 kHz (with a tolerance of 20% at 125 Hz). Compared with the CA, the ON showed a higher RT at 125 Hz before the acoustic treatment, which exceeded the requirements. The ON showed a larger decrease than the CA in both the 5-bed room (28.9% vs. 40.5%) and 2-bed room (46.7% vs. 51.0%) at medium frequencies after installing the acoustic ceiling tiles. However, there was a smaller change at low frequencies (125–250 Hz) in both the 5-bed rooms (40.0% vs. 23.8%) and 2-bed rooms (35.1% vs. 23.4%), possibly as a result of the plaster ceiling in the ON having better sound absorption at low frequencies than the bare concrete ceiling in the CA originally. In addition, significant changes were found in the small patient room with 2 beds, possibly due to their initially relatively higher RTs.

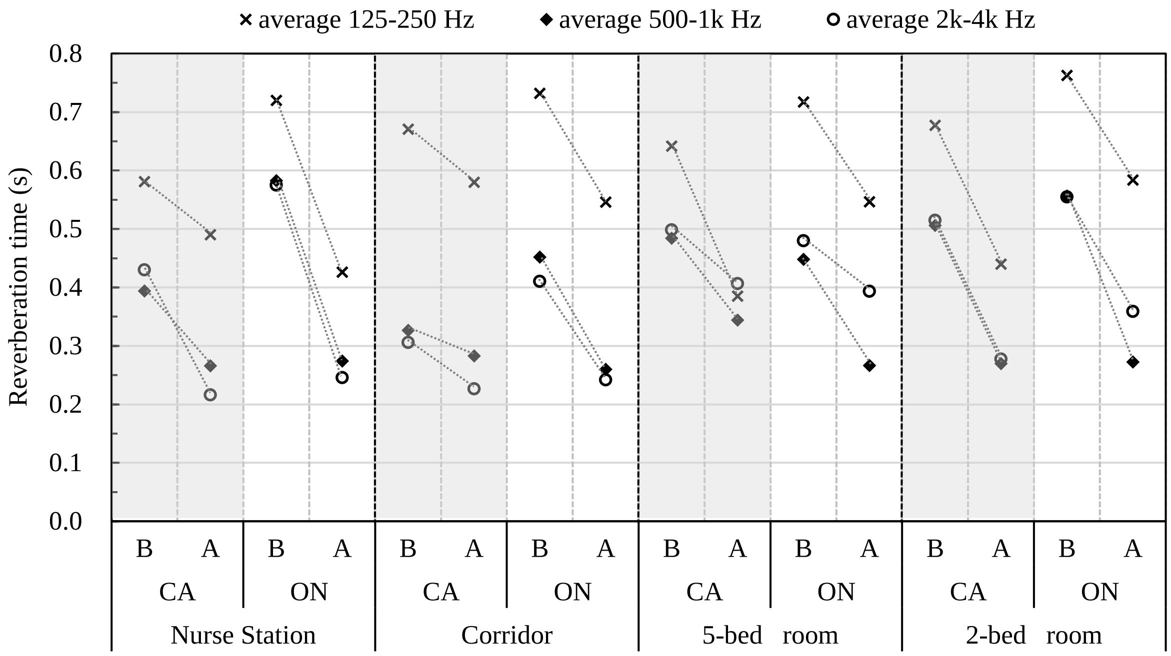


Fig. 3. The comparisons of reverberation time at each location before and after acoustic treatment
Note: 'B' indicates before treatment, 'A' indicates after treatment

3.2 Effect on equivalent noise levels during daytime and nighttime

According to the Chinese National Standard [23], the background noise level of a patient room should not exceed 40 dB(A) during the day and 35 dB(A) at night. However, as shown in Fig. 4, the noise levels of the two unoccupied patient rooms in the original state dramatically exceeded the limit, especially during the day with more medical activities taking place. As expected, the background noise levels in the two patient rooms met the standard after changing the door and windows. The L_{eq_day} in the two rooms declined sharply by over 10 dB(A) ($p<0.01$), and the L_{eq_night} declined by approximately 6 dB(A) ($p<0.01$). Meanwhile, a higher L_{eq_day} was found in the 2-bed room located at the middle of the corridor (see Fig. 1) with more activities compared with the 5-bed room at the end of the corridor.

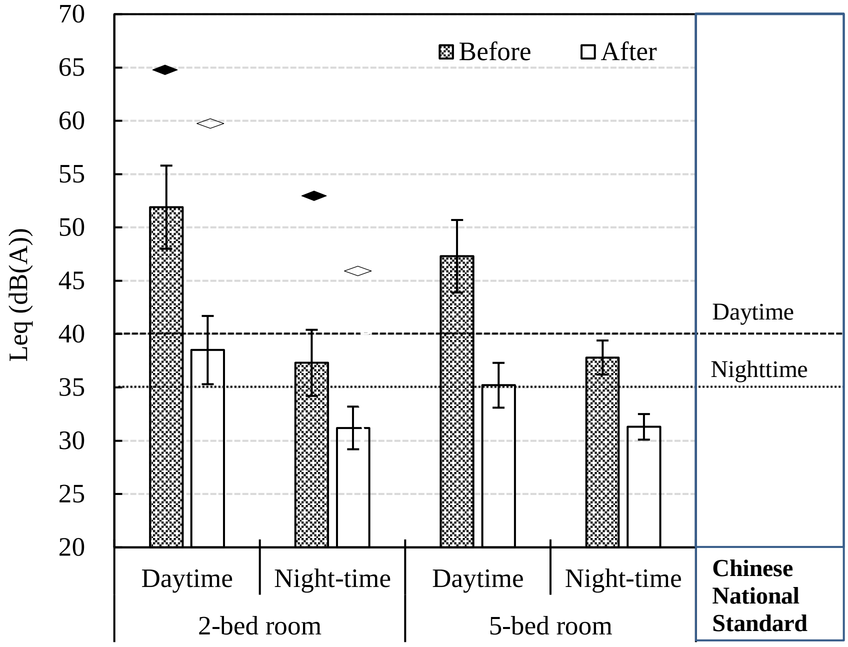


Fig. 4. The comparisons of L_{eq} in the unoccupied patient rooms of CA before and after acoustic treatment

notes: "◆" = $L_{eq\_daytime}$ when occupied by patients, "◇" = $L_{eq\_nighttime}$ when occupied by patients

As shown in Table 2 and Fig. 4, the L_{eq} was significantly higher in a fully occupied room than in the same empty room in CA during the daytime or nighttime. Additionally, fewer differences were found in the L_{eq}, L_{10}, and L_{90} of occupied rooms during the daytime. This is largely due to the noise produced by patients and their relatives inside the room by talking, watching TV, engaging in general activity, etc. In the nighttime, when patients slept and their activities stopped, a similar result was found, with a 5 dB(A) decrease in L_{eq} in the occupied room after the renovation.

As the main workplace for nurses, nurse stations are always crowded with people and tend to be noisier than the patient rooms and corridors during the daytime. Before the acoustic treatment, the daytime L_{eq} of the nurse stations reached 66.9 dB(A) in the ON and 67.8 dB(A) in the CA, and the daytime L_{10} was over 70 dB(A) in both the ON (70.3 dB(A)) and CA (71.8 dB(A)), which were highly affected by the frequency of high noise events. Noise events with a L_{eq_1min} over 70 dB(A) occurred 240 times in the ON and 152 times in the CA. These values were much higher than those tested in the corridor and patient rooms. After the acoustic treatment, the L_{eq} of the nurse station in the CA decreased by 4.6 dB(A) (p<0.01) and 7.4 dB(A) (p<0.01) during the daytime and nighttime, respectively, and the nurse station in the ON by 8.6 dB(A) (daytime, p<0.01) and 13.5 dB(A) (night-time, p<0.01). The number of high noise events also decreased sharply in both departments after acoustic treatment.

Lower noise levels, based on L_{eq}, L_{10}, L_{90} and the number of high noise events, were found in the corridor compared with the nurse station in both wards. A more significant reduction in noise levels after acoustic treatment was found at night than during the day. L_{eq} declined by approximately 5 dB(A) (p<0.01) in the two corridors after the acoustic treatment. Meanwhile, greater changes were found in the background noise level (L_{90}) (p<0.01) compared with the instantaneous peak noise level (L_{10}) (p<0.01) after the acoustic treatment.

However, the number of high noise events decreased sharply at all three locations in the two departments after renovation. Approximately ten high noise events were identified during the daytime with L_{eq_1min} over 70 dB(A) and, according to the onsite observation, were mainly due to medical trolleys, indicating that the sound of the trolley could not be absorbed effectively by installing acoustic ceiling materials because of the loud structure-borne noise produced by the wheels on hard floors. Replacing these trolleys with a silent model and installing a flexible floor or carpet is likely a more effective solution for reducing trolley noise.

Table 2. The comparisons of L_{eq}, L_{10}, L_{90} (dB(A)) and the number of high noise events with L_{eq_1min}>70 dB(A) before and after acoustic treatment

			L_{eq}		L_{10}		L_{90}		No. of L_{eq_1min}>70 dB(A)	
			daytime	night-time	daytime	night-time	daytime	night-time	daytime	night-time
2-bed room	ON	Before	61.0±3.3	51.2±6.7	63.9	53.3	56.8	46.9	42	0
		After	58.8±5.1	45.9±5.1	62.4	46.8	52.6	41.4	10	0
		Diff. (*p*)	2.2 (.000)	5.3 (.000)	1.5 (.000)	6.5 (.000)	4.2 (.000)	5.5 (.000)	32	0
	CA	Before	65.3±4.3	57.3±4.2	69.2	61.3	57.8	51.4	77	11
		After	61.1±3.9	51.6±4.3	64.6	54.0	54.9	45.5	11	0
		Diff. (*p*)	4.2 (.053)	5.7 (.000)	4.6 (.000)	7.3 (.000)	2.9 (.087)	5.9 (.000)	66	11
Corridor	ON	Before	60.6±3.9	48.3±4.9	64.1	53.8	54.0	40.2	36	6
		After	58.5±3.2	43.7±3	60.7	45	52.4	38.4	10	0
		Diff. (*p*)	2.1 (.000)	4.8 (.014)	3.4 (.000)	8.8 (.000)	2.6 (.093)	1.8 (.237)	26	6
	CA	Before	64.5±4.5	52.9±1.3	68.0	53.8	56.0	50.9	48	0
		After	59.5±5.7	46.7±2.8	63.1	47.3	47.1	42.4	13	0
		Diff. (*p*)	4.9 (.000)	6.2 (.000)	4.9 (.000)	6.5 (.000)	8.9 (.000)	8.5 (.000)	25	0
Nurse station	ON	Before	66.9±5.5	52.7±3.6	70.3	56.8	60.4	45.6	240	0
		After	58.3±7.2	43.0±2.5	62.5	47.2	48.7	36.6	12	0
		Diff. (*p*)	8.6 (.000)	9.3 (.000)	7.8 (.000)	9.6 (.000)	11.7 (.000)	11.0 (.000)	228	0
	CA	Before	67.8±6.4	55.2±2.5	71.8	57.2	54.6	52.3	152	0
		After	63.2±8.0	47.8±4.5	68.3	52.0	47.9	43.4	14	0
		Diff. (*p*)	4.6 (.000)	7.4 (.000)	3.5 (.000)	5.2 (.000)	6.7 (.000)	8.9 (.000)	138	0

Note: a. Values of L_{eq} are expressed as the mean±S.D. (standard deviation).

b. Daytime: 06:00~22:00, nighttime: 22:00~06:00.

3.3 Effect on SPL variation over 24 hours

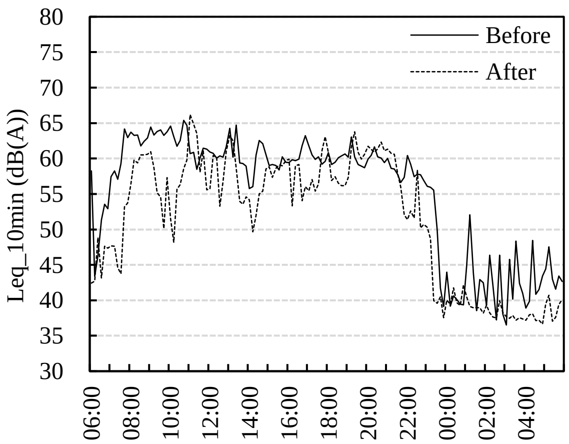
Fig. 5 illustrates the variations over a 24-hour period in the L_{eq_10min} averaged over three days before and after renovation. All the curves show dramatic increases at the beginning of the daytime period (06:00~08:00) followed by decreases from 22:00 to 23:30. Significantly lower SPLs were found in each area after renovation, especially at night.

As shown in Fig. 5a-5b, more remarkable differences in noise levels were found in the ON patient room during the nighttime. The 2-bed patient room experienced large fluctuations in noise level from 24:00 to 07:00 before the renovation, while the noise level was relatively flat after the installation of sound-proof doors and windows. Another difference was found at the beginning (22:00~01:00) and end (06:00~07:00) of night, during which most patients were sleeping but medical activities in the corridor continued.

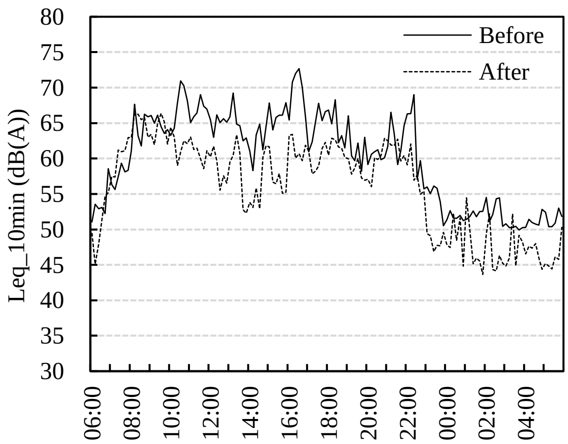
A door with better sound-insulation performance may decrease the influence of noise from the corridor and extend the ‘quiet period’ for patients’ sleep.

As shown in Fig. 5c-5d, relatively lower noise levels and flatter trends were found at the ON nurse station, whereas large fluctuations can be found at the CA nurse station over 24 hours, with peak noise levels above 75 dB(A) occurring a few times during the daytime. Despite the change in acoustic conditions, the SPL variation was closely associated with routine activities of the department based on the researcher’s onsite observation and conversations with staff and patients. A similar tendency of noise level variation was found between the two curves, while a lower noise level with an approximately 5 dB(A) difference was found after acoustic treatment. According to field observations, the behavioral state of medical staff at the nursing station did not change over time, especially during the daytime peak hours of 08:00~12:00 and 14:00~18:00.

As shown in Fig. 5e-5f, because of the spatial connection between the corridor and nurse station, noise levels in the corridor and nurse station can influence each other substantially, as evidenced by very similar trends in SPL variation over time in the CA corridor and nurse station. Additionally, due to the provision of temporary beds in the CA, nursing work had to be carried out in the corridor. As a crowded open space connecting with nurse station, a relatively higher SPL and larger fluctuations can be found in the CA during both daytime and nighttime. However, more significant improvement can be found in the CA corridor after the acoustic treatment, similar to that measured in the nurse station of the CA. As a crowded opening space connecting with the nurse station, the CA corridor still obtained a higher SPL during the day and night after the renovation.



(a)



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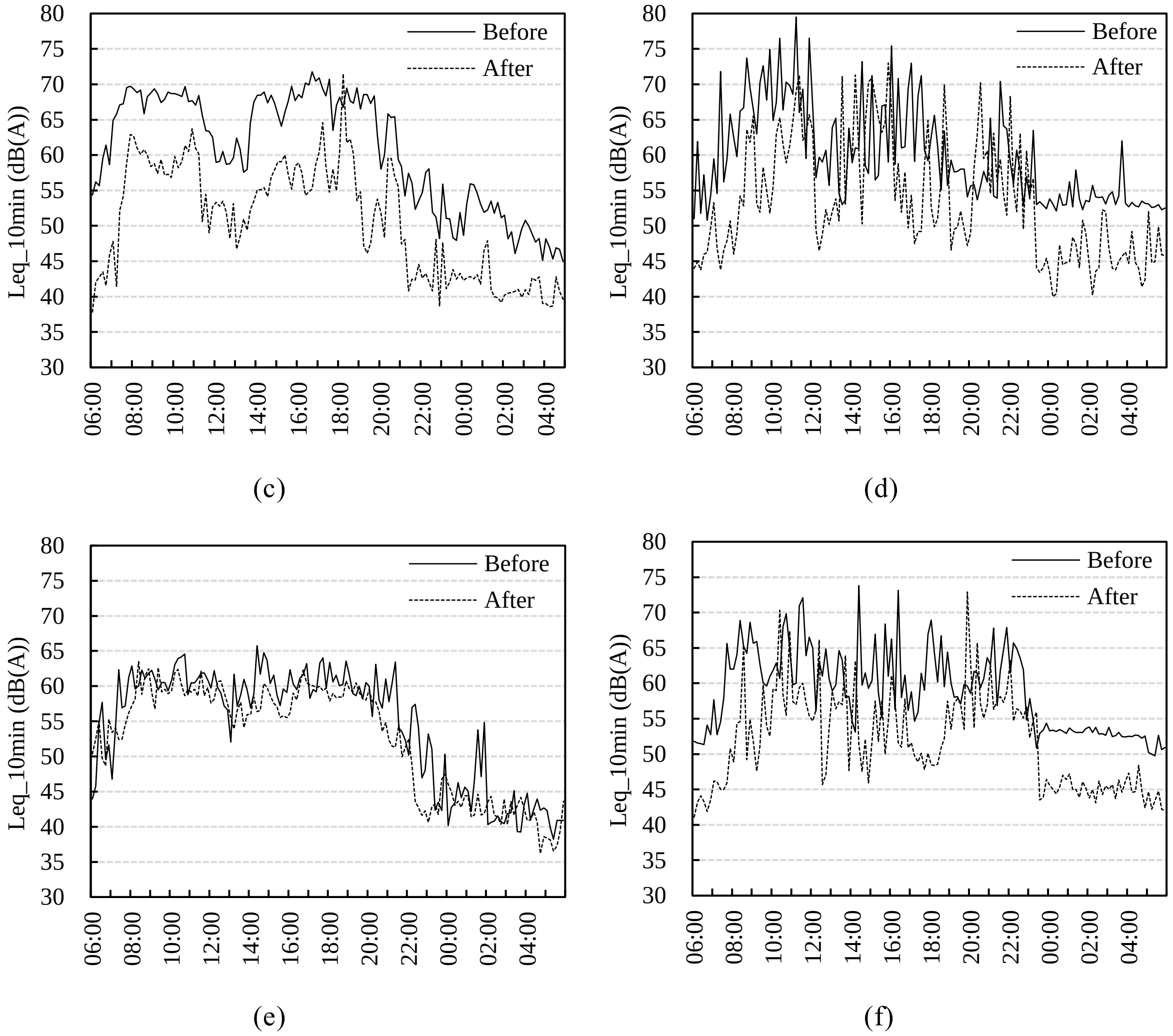


Fig. 5. The comparison of L_{eq_10min} variation over 24 hours at different locations before and after acoustic treatment, (a) 2-bed room of ON, (b) 2-bed room of CA, (c) nurse station of ON, (d) nurse station of CA, (e) corridor of ON, (f) corridor of CA

3.4 Effect on sound spectrum

Fig. 6 shows the 1/3 octave spectrum measured in each location before and after renovation. A similar trend was found among the three tested locations before acoustic treatment. The dominant frequencies ranged from 250 Hz to 1 kHz, and the peak levels, between 55 dB and 60 dB, were at approximately 630 Hz. The spectral pattern was similar to that of human speech, indicating that talking might be the primary noise source in the patient room, nurse station and corridor. The main noise source was found to be largely different from that in the ICU. Two previous studies conducted in ICU wards indicated that high frequency noise over 1 kHz dominated the sound spectrum, which was largely due to loud noises from medical equipment and activities [21, 50].

As expected, a remarkable change can be found in frequencies over 250 Hz with a 3~7 dB decrease after the renovation. This could be highly related to the sound absorption performance of the acoustic ceiling for each frequency band, as the material is effective mainly for frequencies above 250 Hz. Unexpectedly, significant gaps with an approximately 8 dB difference were found at a frequency of approximately 630 Hz in the nurse station. The possible reason is discussed in section 4.1.

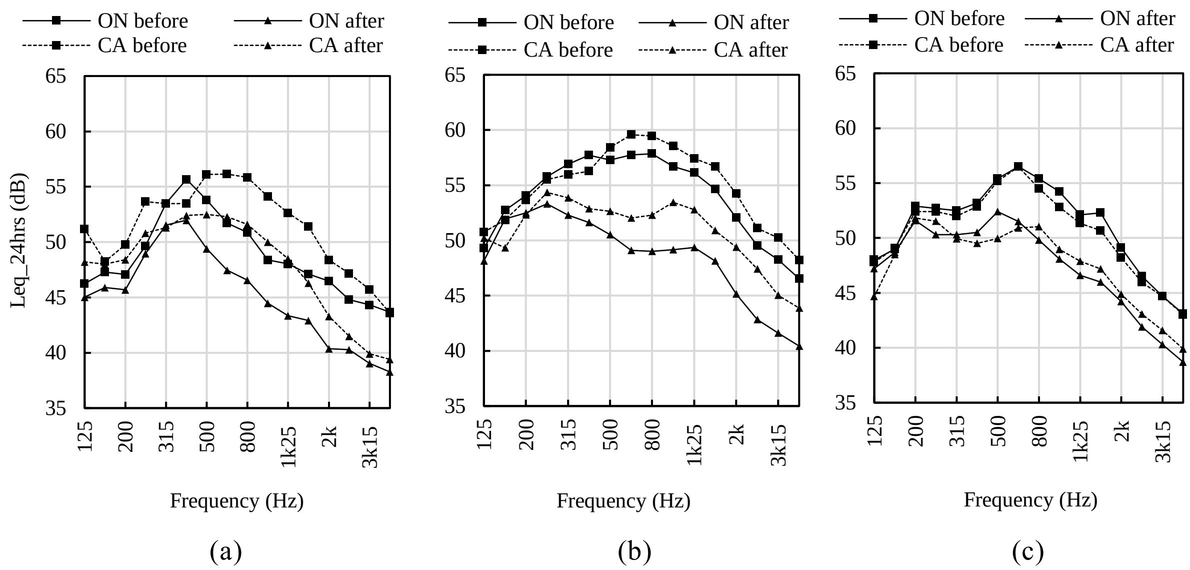


Fig. 6. The comparison of the 3-day-average spectrum over 24 hours before and after acoustic treatment, (a) 2-bed rooms, (b) nurse stations, (c) corridors

3.5 Effect on users' subjective evaluation

As shown in Fig. 7a, the placement of temporary beds in the CA corridor made it a noise-sensitive area. Before the acoustic treatments, over 60% of participating patients living in the wards considered noise to mainly originate from both the interior of the ward and the corridor, followed by the outside (see Fig. 7a). After changing the door and windows to a soundproof one, a smaller number of patients from the two renovated wards considered the main sources of noise to be the corridor and outside.

To a certain extent, acoustic treatment improved the perception of patients and staff, but there was no significant change in the identification of the main noise sources. In agreement with the frequency analysis in Fig. 6, 'patients talking' was always the major noise source identified by almost all of the patients and staff. However, significant decreases were found in the noises originating from trolleys moving and footsteps, which mainly came from the corridor.

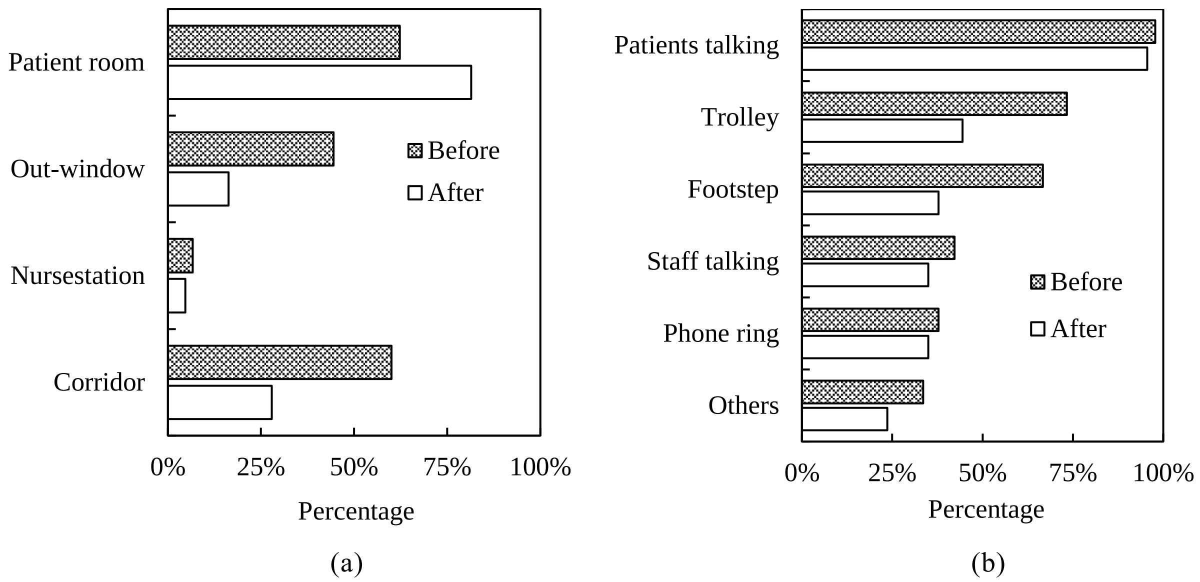


Fig. 7. Comparison of noise evaluated by patients in the CA ward before and after acoustic treatment, (a) noise source locations, (b) major noise sources

In terms of subjective noise level and impacts of noise on patients and staff, participants were divided into three groups, namely, patients from the corridor (CP), patients from the ward (WP) and medical staff (MS). As shown in Fig. 8, both patients (p<0.01) and staff (p<0.05) considered lower noise levels to be significantly reduced after the acoustic treatments. In addition, 48.5% of the nurses indicated that improvement in the acoustic environment was noticeable after acoustic treatment.

Less noise impact on participants' conversation, emotion, sleep and work efficiency was found after the acoustic treatment. The negative impact of noise on the sleep of patients decreased significantly, especially in the CP group, with a decrease in rating from 4.1 to 3.2. It should also be noted that CP's rating of emotional impact declined from 3.6 to 3.1. No significant difference was found in the 'recovery' of patients according to their evaluation, although a relevant study indicated that negative emotions and sleep disruptions caused by noise may have a negative effect on the recovery of patients [51]. On the other hand, lower ratings of noise impact on conversation and work efficiency among MS represented a positive effect on general healthcare activities, which can be related to lower noise levels and better confidence in understanding speech after replacing the ceiling material.

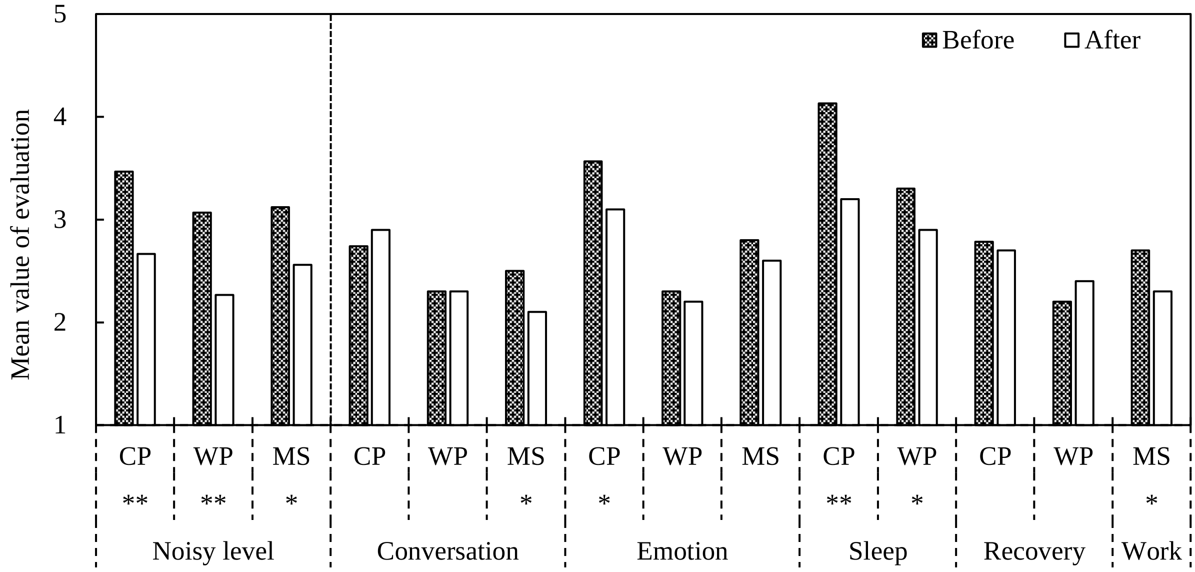


Fig. 8. Comparison of noise level and its impacts on participants before and after acoustic treatment

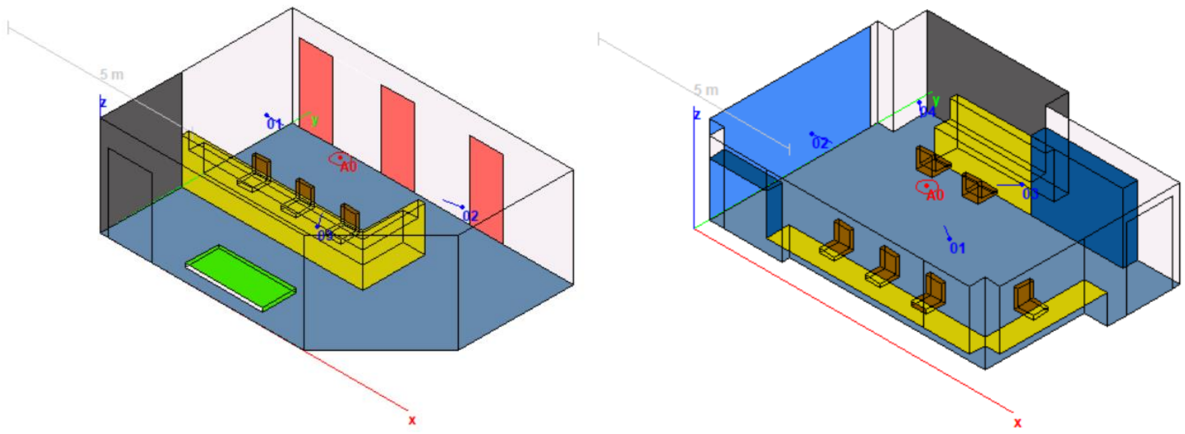
Note: for noisy level, 1='very quiet', 5='very noisy'; for impact level, 1='not at all', 5='extremely'

4. DISCUSSION

4.1 Influence of sound field changes on users' behavior

As an open-plan work environment, the nursing station serves to maintain workflow and is the setting for frequent social interactions and teaching and learning activities. Meanwhile, there are many additional sound sources, including alarms, pagers, telephones, and other equipment, making the nurse station noisy, crowded and busy. Patients and staff must often raise their voice level during their communication. This makes the nurse stations the noisiest area in the wards during both daytime and nighttime, with noise levels exceeding those measured at the nurse stations by approximately 10 dB(A) in two hospitals in the USA [46, 52]. Changing the ceiling from a hard surface to an absorptive face was found to be more effective in decreasing noise levels in the nurse station than in the corridor and patient rooms. Among all the noise sources, the decrease in noise due to talking was the most remarkable, with an approximately 8 dB difference at a frequency of approximately 630 Hz, similar to the spectrum of speech (see Fig. 6). This might indicate that the acoustic ceiling can not only absorb reflected sound energy, resulting in a lower RT but also make the nurse station a quieter space with a higher speech transmission index (STI). According to the questionnaire (Fig. 8), staff members could take advantage of speaking ($p<0.05$) in a lower voice and having a higher working efficiency ($p<0.05$).

To clarify the difference between the theoretical impact and actual impact of installing an acoustic ceiling on the sound field, acoustic models of the two nurse stations were built in CATT Acoustic v9.1, as shown in Fig. 9. One sound source was placed in the middle of each nurse station, and a receiver was placed at the same position with the sound level meter fixed. After changing the ceiling to the absorptive ceiling with an NRC of 0.75, the STI increased by 13.0% from 0.69 (a 'good' rating) to 0.78 (an 'excellent' rating) in the CA according to the simulation. A more remarkable increase of 36.2% from 0.58 ('fair') with the plaster panel ceiling to 0.79 ('excellent') can be found in the ON. By matching with the field measurement data in the nurse station of the CA (ON), as shown in Table 2, the sound emission level from the source was calculated to be 55.3 dB (51.1 dB) at 630 Hz, with the receiver measuring a level of 59.6 dB (57.7 dB) after reverberation. With the same emission from the sound source remains and an absorptive ceiling, the sound level at the receiving point was calculated to be 57.8 dB (52.4 dB). However, the measured data at 630 Hz were 52.6 dB (49.0 dB), 4.8 dB (3.4 dB) lower than the simulated data, indicating that the emission of the sound source in the CA (ON) was further reduced by 4.8 dB (3.3 dB) relative to the calculation.



(a) (b)

Fig. 9. CATT Acoustic models of (a) CA nurse station, (b) ON nurse station

On the other hand, changing the door between the corridor and patient room to a soundproof one was found to have a positive impact on the patient's sleep pattern. Although there is no standard or code-limited noise level in hospital corridors, corridors were measured as a noise-sensitive area with noise levels above 60 dB(A) in this study and in a number of hospitals around the world [44-46, 52]. In addition, similar noise sources such as frequent traffic, footstep, trolley movement, and talking on the phone in corridors were observed [46, 52]. According to the site observation, sound sources from the corridors could be perceived by the patients in their room through the regular wooden door. As expected, this issue was effectively alleviated by replacing the doors between the internal patient room and the corridor with high-performance acoustic doors. Larger differences were found during the nighttime from 22:00 to 24:00, while most patients were sleeping time but medical activities in the corridor continued. According to the interviews, patients in the rooms with acoustic treatments reported an earlier sleep time and fewer awakenings during the nighttime compared with those in the untreated rooms.

4.2 Acoustic recommendations for hospital wards

As suggested by a number of studies, various noise control strategies can improve hospital environments for both patients and staff [37-43, 47, 53-55]. Installation of sound-absorbing ceiling tiles was considered the most feasible approach to reduce indoor noise levels [56]. The results of this study provided evidence that compared to ceilings with a hard surface, the installation of sound absorptive ceilings can not only reduce overall noise levels in patient rooms, corridors and nurses' stations but also improve the reverberations in nurse stations. Staff members in this study reported some positive outcomes on spoken conversations and working efficiency. One similar study also indicated that a lower noise environment is beneficial to the productivity of medical staff, particularly when they are performing cognitive tasks such as charting and typing reports [47].

Additionally, adopting the use of doors with better sound insulation performance in patient rooms significantly decreased the noise impact from the corridor and extended the 'quiet period' for patients' sleep during the nighttime. For postoperative patients, better sleep quality may help relieve postoperative pain, increase wound healing efficiency, reduce the amount of medicine used, and shorten the postoperative recovery cycle [57-61].

In addition to acoustic treatments, behavioral modification programs, staff education and strict management can be considered effective ways of eliminating man-made noise [37-43, 47, 53-55]. In this study, 53.5% and 44.0% of patient and staff members, respectively, were satisfied with the acoustic condition after the treatment. The rest of the participates insisted that the acoustic environment of the ward still needs to be further improved; restrictions on the speech level, the number of visitors, and the visiting time period were the primary recommendations of both patients and staff.

In addition, compared with replacing the door, windows and ceiling of the ward, indoor soundscape design may be a more feasible approach to improve the sound environment for both new and existing hospital wards. Evidence has also shown that the introduction of natural sounds resulted in positive effects on anxiety levels and the reported tranquility of patients [68].

4.3 Limitations and future work

In summary, this experiment comparing conditions before and after renovations provided evidence that installing an acoustic ceiling and sound insulating door can reduce the RT and noise level in ward areas and reduce the impact of noise on patients' sleep and psychological index and staff's work efficiency. However, the above results were only based on acoustic measurements and questionnaires. More physiological indicators related to patient recovery need to be evaluated under different acoustic conditions. Our next study, therefore, aims to explore the influences of different acoustic conditions on the physiological states of patients and staff by conducting a controlled trial.

5. CONCLUSIONS

A comparative study was carried out to quantify the effectiveness of acoustic treatments, including installing an acoustic ceiling and soundproof doors and windows, on the reverberation time, noise levels and users' evaluation and behavior at different locations of wards during normal operations in a general hospital in China.

It was shown that there was a certain degree of improvement in reverberation time in the patient rooms, nurse stations and corridors after the installation of the acoustic ceiling. T_{30} (500 Hz–1 kHz) dropped by 29%~47% in the patient rooms and 13%~43% in the corridors. Larger decreases of 33%~53% were found in the nurse stations.

Noise level measures, including L_{eq}, L_{10}, and L_{90}, dropped significantly ($p<0.01$) by 5~13 dB(A) in the corridor and nurse station, with a smaller number of high noise events with L_{eq_1min} over 70 dB(A) that can negatively impact conversation. Although the difference in internal noise level became small in the occupied patient rooms during the daytime, a significant decrease of approximately 5 dB(A) ($p<0.01$) was found during the nighttime.

Despite the change in acoustic conditions, the SPL variation was closely associated with routine activities of the department. A similar tendency of noise level variation was found before and after the acoustic treatment, while a lower noise level with an approximately 5 dB(A) difference was found after acoustic treatment in the same time period.

Due to the absorption coefficient of mineral fiber tiles with high performance at middle and high frequencies, a significant 3~5 dB decrease was found for frequencies above 250 Hz after renovation. A more significant, approximately 8 dB difference, was found at a frequency of approximately 630 Hz in the nurse station, indicating that the acoustic ceiling can not only absorb reflected sound energy but also make the nurse station a relatively quiet space with a relatively higher STI.

Questionnaire results indicated that the subjective perception of noise level of both patients and staff decreased, and 48.5% of the nurses indicated that improvement in the acoustic environment was noticeable after acoustic treatment. Less negative ($p<0.05$) impacts of noise on participants' conversation, emotional state, sleep and work efficiency were found after renovation.

Medical staff at the nurse stations could take advantage of speaking in a lower voice and having a higher working efficiency. Meanwhile, adopting a door in the patient room with better sound insulation performance significantly decreased the noise impact from the corridor and extended the 'quiet period' for patients' sleep during the night-time.

In addition to acoustic treatments, behavioral modification programs, staff education and strict management can still be considered effective ways of eliminating man-made noise. In addition, compared with replacing doors, windows and ceilings, indoor soundscape design may be a more feasible approach to improve the sound environment for both new and existing hospital wards.

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