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The Role of Acoustics in Architectural Design of Medical Centers: A Review

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Abstract
Today, medical centers are considered to be healing environments. A healing environment provides a space with a positive effect on its occupants. Architecture has an undeniable role in creating such an environment. Comfort factors should be carefully considered when designing health centers. Amongst these factors, acoustic comfort in hospitals plays a prominent role. The adverse effects of noise on patients have been well documented in many studies. Architectural design can have a major impact on the quality of a hospital's acoustic comfort. In this article, studies related to the acoustic design of therapeutic buildings are reviewed. First, different approaches to building acoustic analysis will be reviewed. Then, architectural approaches for controlling noise pollution in medical centers are discussed. Common criteria concerning acoustic comfort in healthcare spaces are introduced. Major acoustic annoyance factors in medical centers are discussed and some potential solutions are presented. This review shows that factors such as site selection, arrangement of different sections, facilities, internal and external noise sources, geometry and structure of the interiors and construction materials have a direct impact on the acoustic comfort of the hospital. General guidelines in acoustical design of medical centers are presented. Some psychological and mental factors associated with acoustic annoyance have also been introduced.
Keyword: *Medical center, architecture, acoustic comfort, noise, construction materials*

Introduction
Today, medical centers are considered as healing environments. A healing environment provides a space with a positive effect on its occupants. One of the most significant aspects of a healing environment is acoustic comfort. Although architectural design is not the only factor in providing acoustic comfort, it plays a key role in this regard. The World Health Organization (WHO) recommends a maximum of 35 and 30 decibels of noise in patient rooms for day and night, respectively. Many studies show that not only is the noise level of hospitals much higher than the WHO recommendation, but also the poor acoustic conditions of hospitals are getting worse continuously [3, 22]. According to a study fulfilled in 2005, since 1960, daytime and night time noise in hospitals have risen up to 200% and 400% respectively [3]. Each hospital zone has its own acoustic condition. This can be due to different patient conditions, number of occupied beds, number and type of equipment and facilities available as well as the architecture of the space. Acoustic comfort in a medical environment can help reduce blood pressure, improve sleep quality, reduce the use of painkillers, reduce stress and improve staff performance and their job satisfaction. High noise levels in medical centers can lead to sleep disorders, high stress, increased recovery period, excessive anxiety, physiological symptoms, increased respiration rate and elevated heart rate in patients. More than 60% of staff members of emergency wards in hospitals consider the noise problem to be a serious and important problem. More than 80% of work interactions of a head nurse in emergency ward are carried out in real time (through face to face interactions or phone calls). Furthermore, around 70% of cases of medical mistakes can be due to multitasking or sudden delay in an ongoing task caused by outside factors [24].

Using a proper architectural design, it is possible to reduce noise pollution which can have adverse effects on patients' health [1]. Noise pollution is one of the largest stress factors for patients and staff members in hospitals. Findings have shown that reducing the noise in medical centers has resulted in increased patient satisfaction, improved sleep quality and reduced blood pressure in patients while also improving the effectiveness and efficiency of staff members [1, 2]. Nowadays, hospitals all around the world have undesirable conditions when it comes to acoustic comfort [3]. Studies in Iran have shown that noise

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pollution in hospitals is above the standard levels [4, 5].

Unfortunately, the importance of hearing and noise is often ignored during normal architectural designs. However, it should be noted that, in humans, hearing is the last sense to stop working before sleep and the first one to restart after waking up [6]. Despite of this fact, visual comprehension usually engages all the minds of architectural designers so much that the acoustic aspects of the design are ignored. [7, 8].

Architectural design process is often based on the desired applications and needs. Sometimes, the requirements of a plan are dictated by standards. Mandatory and optional items should also be considered by the designer when designing a specific building. It goes without saying that architectural design should be based on the future applications and needs. In other words, architecture should provide users with sufficient comfort and necessary conditions. Therefore, during the architectural design of a building, all factors and parameters affecting users' comfort should be considered. Acoustic considerations are also one of these affecting factors. The acoustic properties and requirements of different buildings such as movie theaters and concert halls, medical centers, classrooms, libraries, hotels, markets, office buildings and residential buildings are often different [9-12]. Despite the lack of direct and conscious attention toward acoustic quality of a building, this equality is one of the important and affective realities of any architecture [13-15]. In the following, important aspects of acoustic comfort are briefly introduced.

Necessary conditions for high acoustic quality of a closed space include:

a) Proper sound distribution: The presence of sound concentration points or blind spots can lead to creating echo and significant reduction in acoustic quality. Figure 1 depicts a sample of sound distribution in a room [6]. Sound loudness is expressed in terms of sound pressure level (SPL) parameter. This parameter is in logarithmic scale and is expressed in decibels (dB). The human auditory system has different perceptions of SPL at different frequencies. For this reason, SPL is usually filtered at different frequencies according to the human hearing system. This filtered SPL is expressed in terms of dB (A). Since the SPL is a function of time, in order for the sound level to be expressed in a single number, LA_{eq} is defined to represent the average of the SPL with an equivalent amount of energy.

b) Optimized background noise level: The optimum amount of background noise depends entirely on the use of the room and is recommended by the standards. Background noise as one of the main input parameters must be considered from the beginning of the acoustic design of a building. It should be noted that the very low background noise does not necessarily provide acoustic comfort. Near-zero background noise in anechoic chamber (used for laboratory purposes) can be horrific and annoying. In addition, the presence of a level of background noise can improve the speech privacy.

c) Reverberation time (RT): It is the most important parameter related to sound quality. Its normal value is determined by space usage and is usually expressed by standards. RT is the time in which the largest amplitude of the sound in a closed space is reduced by 60dB after the sound source stops. Figure 2 shows the optimal reverberation time values for different spaces based on space volume [6]. Generally, the two parameters of SPL and RT are not directly related to each other and are independently investigated.

Among the above parameters, the role of noise in the therapeutic areas and especially the patient room is more important. In the remainder of this article, acoustic analysis methods as well as some concepts of building acoustics will be briefly introduced. Then, the building acoustics of therapeutic spaces will be considered.

Table 1 lists the recommended values of SPL and RT for different zones of a hospital.

In Table 1, recommended RTs are referred to mid-frequencies, i.e. 500 or 1000 Hz. Occupancy of the rooms are assumed 67%. For large room volumes, RT is decreased in lower frequencies, while in small rooms, RT is less dependent to frequency. If the primary purpose is to control noise, RT should be reduced as much as possible. But if speech clarity is also intended, the RT should be kept within the allowed range.

2. Acoustic Analyses of Architectural Spaces

Geometrical methods, statistical calculations and methods based on wave theory are three usual approaches used for acoustic analysis of architectural spaces [4, 6].

2.1 Geometrical Methods

In this method, it is assumed that the sound wave is propagated and reflected like a beam of light. The main problem of this method is that it ignores the wave nature of sound. Sound waves with different frequency and wavelength are considered similar in this approach while they are different in reality. Reflection amount, as well as sound transmittance or absorption in a barrier is fully dependent on wavelength. Sound insulations and barriers can easily stop sound waves with short wavelengths (high frequencies), while high wavelength (low frequency) sounds can't be fully controlled using sound insulation.

2.2 Statistical Methods

These methods calculate the decay rate of sound based on average statistical free path of sound waves during continuous impacts and absorptions in a closed space.

2.3 Methods Based on Wave Theory

These methods require the extraction of wave traveling equation in each environment and solving these equations. It is almost impossible to use these methods for complex geometries due to the complexity of resulting equations. However, these precise and cumbersome calculations can be used for small and simple spaces or critically important sites such as audio studios or sound labs.

2.4 Selecting the Proper Method for Acoustic Analysis of Architectural Spaces

Selecting the proper approach among the abovementioned methods for acoustic design of a building depends on such factors as frequency content of the sounds and building's size. Figure 3 shows a qualitative overview of the applicable range for each of these methods [6, 13].

Shape and form of the internal space can greatly affect sound reflection. If the reflected sound reaches the ear in less than 50ms, it can improve sound comprehension. However, with increase in this time (which depends on the form and dimensions of the space), sound and its reflections are heard as echo. Usually, spaces with concave geometry, especially spaces with focal points, can create an echo in the building. In this case, the radius of the concave part and dimensions of the room can affect the echo in the building. It is possible to calculate the critical point for hearing an echo from a sound source in a closed space [6, 13].

The dimensions of a room have a direct impact on the acoustic resonance frequencies of the room. Resonance formation, which is actually a stable standing wave, is an adverse acoustic event. For example, for a cubic room with dimensions of 3.5 meters, standing waves are created at around the frequency of 50Hz which is fully in the hearing range of humans and can cause undesirable acoustic properties in the room. The proper selection of dimensions of small rooms (length, width and height) can have a significant effect on improving their acoustic properties [6, 13].

If a sudden sound, like a balloon explosion, is created in a room, up to 8000 continuous reflections of the sound can reach the ears of a person standing in that room. Number and the strength of these continuous reflections reaching the human ears depend on the geometry and absorption rate of the walls [16, 17]. One of the important parameters in room acoustics is the reverberation time parameter (RT_{60}). This parameter shows the time necessary for the amplitude of the sound wave to decrease by 60 decibels. The first analytical equation for calculating reverberation time was introduced by Sabine [16]. A 60-dB reduction in amplitude is equal to reducing sound wave energy to one-millionth of its original value. This reduction in sound energy due to continuous reflection is different for various surfaces (based on the material and geometry). Furthermore, the reduction in amplitude is not the same at different frequencies. This parameter is directly affected by sound-absorbent properties of the environment. Figure 4 shows a schematic of this interaction [4, 13].

Another parameter determining the acoustic quality of a room is its clarity. This parameter determines the clarity and the ability to separate reflected sounds from subsequent reflections. It can be said that clarity is the opposite of reverberation time which means that increase in reverberation time can result in decrease in clarity. Human brain is unable to separate sound waves and sound reflections reaching the ear with less than 200ms of time difference. If the time between the main sound and its echoes is larger than this value, sound clarity will be distorted. Although this parameter is important in such spaces as lecture halls or orchestra halls, its importance is diminished in some spaces such as hospitals [16, 17].

Based on the building applications, different criteria are used for its acoustic design. In most cases, sound insulation and sound absorption are considered. Sound absorbent materials will play an important role in these cases. These sound absorbents are divided into three categories of porous materials, absorbent panels and Helmholtz Resonator [6, 13].

3. Measures of Acoustic Comfort in a Healthcare Center

The acoustic comfort of a building depends on many factors such as site location, layout of spaces, geometry and construction material. There are various acoustic criteria for quantifying different aspects of acoustic comfort. In the following, some of important measures as well as their optimum values for healthcare buildings are explained.

3.1. Noise Reduction Coefficient (NRC)

NRC is a number between zero and one, indicating the ability to absorb sound in the speech frequency range (250-2000 Hz). NRC values less than 0.5 and greater than 0.8 indicate poor sound absorption and high surface absorption, respectively.

3.2 Sound Transmission Class (STC)

STC demonstrates the efficiency of a wall in preventing sound from crossing over. Table 2 gives a better understanding of the concept of STC of a wall.

If there is a lot of noise in the room next to the patient's room, a high STC wall should be used. In general, the interior walls of a hospital should be of STC 35 or above. The STC of walls of very noisy rooms, such as MRI room, may be up to 60. [25]

When designing walls, in addition to acoustic specifications, special attention should be paid to holes, openings and ducts. Any opening on the wall can greatly reduce the wall STC. This also includes doors on the wall. The use of thick sound absorbing panels on walls can have a great impact on reducing ambient noise. If these panels are not permitted for infection control purposes, an impermeable thin coating may be used on the panels.

3.3. Ceiling Attenuation Class (CAC)

CAC specifies the capability of a ceiling to prevent sound from passing. The CAC value in decibels indicates how much the sound of the upper room is attenuated when passing through the ceiling. Ceilings with a CAC of less than 25 are considered to be poor sound barriers, while ceilings with a CAC of 35 or more are excellent barriers to sound penetration. In choosing a proper ceiling, one must distinguish between CAC and NRC. A high value of CAC demonstrates the ability to reduce the vertical transmission of sound while the NRC indicates the amount of sound absorption at the ceiling surface. In the design and construction of the ceiling, materials with high CAC and NRC should be considered.

3.4. Speech clarity

Clarity and intelligibility of speech is closely related to the background noise. Listeners are able to understand speaker's speech only if the voice is sufficiently louder (at least by 15 dB) than the background noise of the location. A minimum difference between speaker's voice and noise is necessary for clarity of speech. The minimum difference for full intelligibility to adult listeners is between 10 to 15 dB, while the necessary difference is 15 dB to 20 dB for children, people with hearing problems or non-native speakers. Various variables including Speech Intelligibility Index (SII), Speech Transmission Index (STI) and Rapid Speech Transmission Index (RASTI) are used to measure speech clarity and intelligibility in a room. The reaction time also affects all these parameters (Table 3) [7, 22].

The Speech privacy is important in some areas of the hospital, such as the reception desk, doctor's office or pharmacy. Due to the inverse relationship between speech intelligibility and speech privacy, acoustic treatments in different areas of the hospital can be totally different. Increasing the background noise level can be implemented to provide speech privacy.

4. Noise Sources

Acoustic discomfort during the day can be caused by various factors, but the most common cause of night acoustic discomfort is due to traffic noise heard through open (or closed) windows. Most sources of noise due to traffic, mechanical equipment, industrial activities and other constant noise sources are present before the start of construction and, therefore, can be identified. The most important method for creating acoustic comfort for patients in the hospital is to increase the distance from noise sources as much as possible. The position of rooms compared to noise sources should also be considered. Point noise sources with some distance to the ground (such as mechanical equipment attached to the buildings) have spherical sound distribution, and doubling the distance reduces the amplitude by around 6 decibels. If the point noise source is placed on the ground, doubling the distance results in around 4.5 dB reduction in amplitude. Noise from linear sources such as roads or railways has cylindrical distribution, and doubling the distance can lead to around 3 dB reduction in amplitude. Environmental factors such as temperature and wind have no effects on noise reduction at short distances, but their effects can be significant at long distances. Figure 5 shows the amount of acoustic discomfort as a function of distance from road or railroad [7, 22]. Table 4
and 5 also show the acoustic and non-acoustic factors affecting acoustic discomfort in order of their importance.

5. Architectural Design for Acoustic Comfort

In this section, general design measures and considerations for hospital acoustic comfort will be addressed.

5.1. Site Selection

The most convenient and effective way to reduce noise in the hospital is to avoid environmental noise sources.
The location of the site selected for the hospital should be sufficiently far from the permanent noise sources. The hospital is recommended to be as far as possible from airports, military bases, railways, freeways, and city bus routes. The orientation of building to environmental noise sources is also important. The concave curved surfaces of the building should not be opposed to the noise source as it creates acoustic focal zones. Given the prevailing wind direction, the noise generated by the wind should be minimized. The topography of the site and its height relative to environmental noise sources can also be a factor. Vegetation usually plays a positive role in reducing noise. Therefore, these should also be considered in site selection and landscape design.

5.2. Space planning

To reduce the cost of separation and acoustic isolation, the layout of different usages should be carefully designed. Decentralizing nursing stations, taking into account dedicated and appropriate spaces for the patient's family and companions, proper distribution of public uses such as toilets, and segregating areas that have many referrals are actions that can be taken.

Single-patient rooms have many other benefits besides providing acoustic comfort.

5.3. Construction Materials and Finishes

Porous acoustic absorbers in ordinary buildings have a great role in reducing noise. Unfortunately, such adsorbents are not allowed in hospitals because of infectious control purposes. The internal surfaces of the walls and the floor of the patients' room should be smooth and cleanable. Vinyl and gypsum surfaces have better sound absorption than stone and tile surfaces. The density and thickness of the walls contribute to the sound insulation. Window is one of the weak acoustic surfaces. The use of multi-glazed windows can make up for this weakness. Acoustic parameters must be considered when designing and constructing walls and ceilings.

The floor must be smooth and without discontinuity to avoid impacts when passing rolling equipment.

5.4. Minimizing Equipment Noise

HVAC system, airflow in ducts and elevators are examples of sound and vibration generating equipment. Some medical equipment like MRI is also noise sources. There are various ways to reduce the noise caused by equipment. Locating equipment as far as possible from noise-sensitive areas, sound insulation of equipment rooms, using low-noise equipment and making use of absorbers and silencers may improve their acoustic performance. Table 6 summarizes solutions for equipment noise reduction.

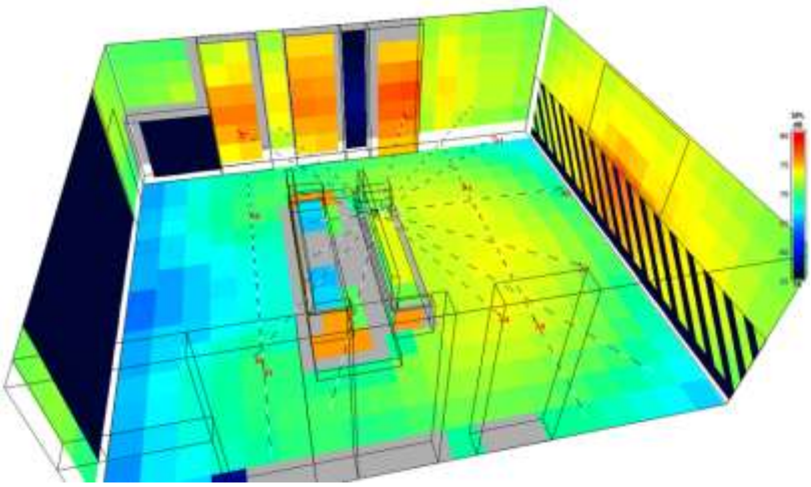

Fig. 1. Sound Distribution in a Room

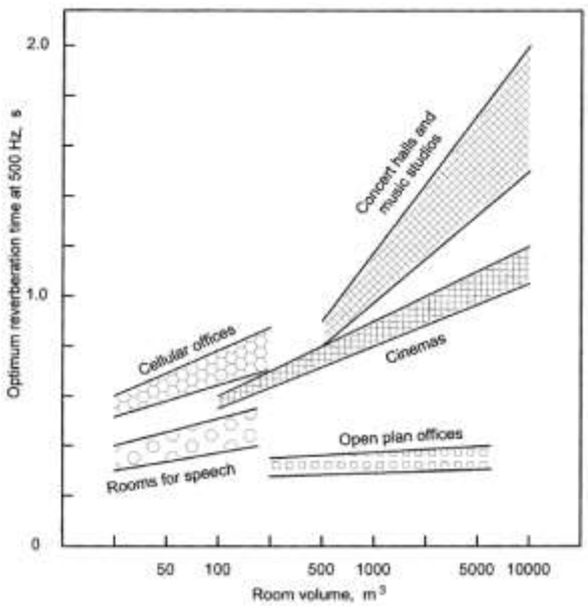

Fig. 2. Ideal Reverberation Time for Different Spaces

Table 1. AS/NZS 2107:2000 Acoustics Requirements for Healthcare Buildings [25]

Zone	CHARACTERISED BY	EXAMPLES	RECOMMENDED MAXIMUM DESIGN SOUND LEVEL, LA_{eq}, dB(A)	RECOMMENDED REVERBERATION TIME (T), s
1	Very quiet space, less communication	Wards	40	0.4 - 0.7
2	Quiet space, one-to-one communication	Casualty areas, Consulting rooms, Dental clinics, Geriatric rehabilitation, Intensive care wards	45	0.4 - 0.6
3	Quiet space, multiple interactions	Nurses stations, Office areas, Surgeries	45	0.4 - 0.7
4	Noisy space, multiple interactions	Delivery suites, Pharmacies, Corridors and lobby spaces	50	0.4 - 0.6
5	Relatively large and noisy space, multiple interactions	Laboratories, Waiting rooms, Reception areas	50	0.4 - 0.7
6	Very noisy space, few interactions	Kitchens, Sterilizing and service areas	50	0.4 - 0.8

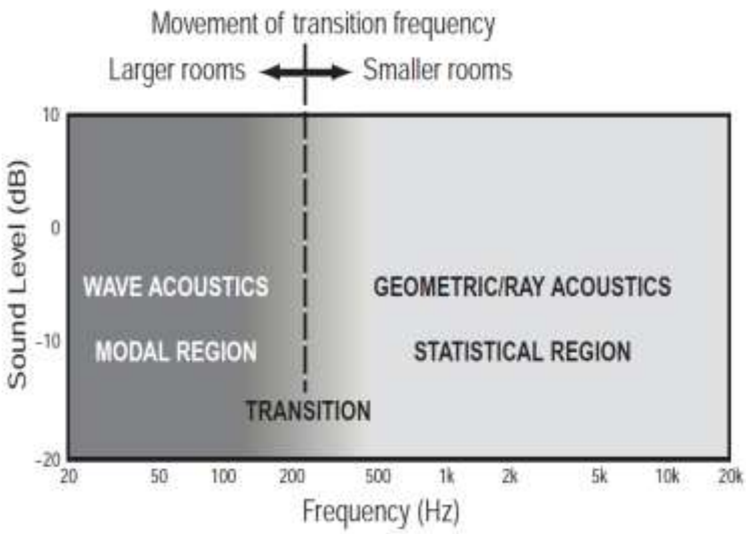

Fig. 3. Application Range of Each Acoustic Analysis Approach

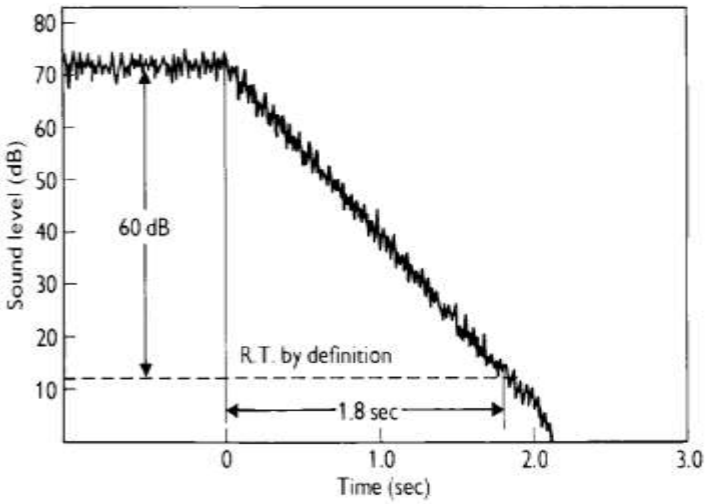

Fig. 4. Sound Decay and Reverberation

Table 2. Acoustic Performance for Walls with Different STC

STC	What can be heard
25	Normal speech can be understood
30	Loud speech can be understood
35	Loud speech audible but not intelligible
40	Loud speech audible as a murmur
45	Loud speech heard but not audible
50	Loud sounds faintly heard
60+	Good soundproofing; most sounds do not disturb neighboring residents [100]

Table 3. Speech Clarity Quality Based on SII, STI and RASTI Parameters [7]

Intelligibility (and its inverse, Speech Privacy)	Speech Transmission Index (STI) or Rapid Speech Transmission Index (RASTI)	Speech Intelligibility Index (SII or SI)
Perfect intelligibility (no privacy)	1.0	100%
Excellent intelligibility	≥0.80	≥98%
Very good intelligibility	0.65–0.80	96%–97%
Good intelligibility	0.50–0.65	93%–95%
Fair intelligibility (poor speech privacy)	0.40–0.50	88%–92%
Poor intelligibility	0.30–0.40	80%–87%
Bad intelligibility (good speech privacy)	<0.30	<80%
Completely unintelligible (confidential)	0	0%

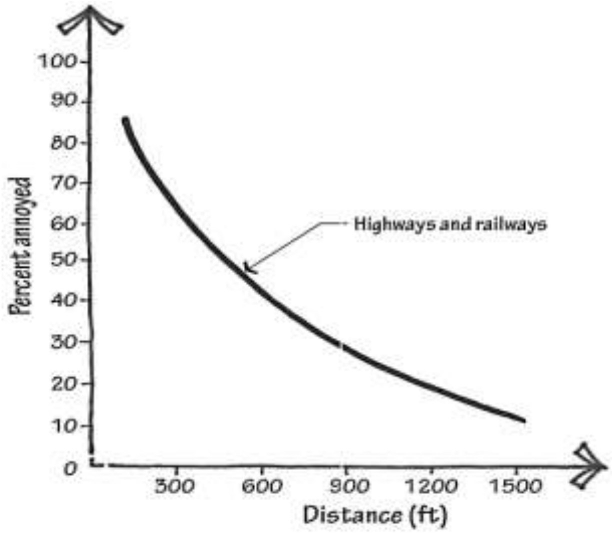

Fig. 5. Qualitative Changes in Acoustic Discomfort Based on Distance from Roads [21]

Table 4. Acoustic Factors Affecting Acoustic Discomfort [7, 22, 23]

Acoustic factors	**Details**
Loudness	Louder noises cause more discomfort
Impulsiveness	Sound sources with shorter duration (less than a second) cause more discomfort. Dog bark sound, impact sounds or jackhammer noise are among this category
Fluctuations	Changes over time (airplane takeoff/landing), amplitude (wind turbines) and frequency (emergency alarms) can cause more discomfort
Tonality	Sound sources which are concentrated in a single frequency or narrow frequency band cause more discomfort (sound of a fan or damaged bearing)
Window state	Although open windows remove the effect of all acoustic considerations, noise in a pleasant weather is more tolerable than noise in bad weather
Rattle	Low frequency noises that cause rattling of walls and windows and easily cross walls cause more discomfort
Audibility	The sound of water dripping causes more discomfort than the sound of running water

Table 5. Non-acoustic Factors Affecting Acoustic Discomfort

Occurrence time	**Noises cause more discomfort during rest hours (nights or holidays)**
Expectations	People that expect acoustic comfort from their location (people in villages or hospital patients) suffer more discomfort
Accountability	When staff members or authorities causing the noise don't cooperate with people, the noise becomes less tolerable.
New sources	Noises which hadn't been experienced before cause more discomfort
Window state	Although people know open windows increases noise levels, the fact that they can't open windows due to loud noises also leads to their discomfort
Attitude toward noise source	Useful or necessary sources of noise (ambulance sirens or noise related to one's profession) are less discomforting than invading or useless noise sources (loud motorcycle noises or noise related to other professions)
Unwanted content	Walking or unrelated and unwanted music can lead to more discomfort (unwanted hearing or loud phone conversations or having to listen to unwanted music)
Constant presence	Constant noise sources (traffic sounds) are more discomforting than temporary noise sources (road construction sounds)
Noise sensitivity	A constant noise can have different effects on different people
Fairness	Being the only one suffering from a noise can make it less tolerable
Fear of risk	Noise sources which are accompanied with risk are more discomforting (such as sound of hunting rifles)
Predictability	Unpredictable noises are less tolerable (like breaking of the sound barrier)

Table 6. Solutions for Controlling Sound Pollution Due to Equipment in a Hospital [2, 5]

Noise source	**solutions**
paging systems	- Using soundless paging system and patient remote care - Using wireless communication systems - Using wireless tracking technologies for equipment, patients and staff members - Adjusting the sound of clinical alarms
facilities and mechanical equipment	- Using suitable fans - Regular maintenance and inspection of filters - Reducing the noise in air ducts - Adjusting air current flow rate
medical equipment	- Placing noise and vibration-sensitive spaces away from MRI equipment location and using sound insulation - Placing no air ducts in MRI room and the nearby environment - Improving sound insulation of walls, floors, ceilings, doors and windows in MRI room

4. Conclusion

Acoustical aspects are usually ignored in many architectural designs. In some spaces like hospitals, acoustic considerations are crucial. Ignoring the acoustic aspects of medical center design can result in serious problems for patients and staff. Adverse effects of noise annoyance on patients have been reported in numerous studies. Although precise building acoustic analysis can be cumbersome, implementation of some general guidelines leads to considerable improvement in providing acoustic comfort. In the present study, after introducing the most important building acoustic parameters, strategies for improving these parameters in hospital design were introduced. The results of this survey show that in addition to proper selection of the site and layout, the materials used in the construction, especially the interior surfaces of the rooms, have a direct impact on the acoustics of the hospital building. Some solutions also focus on the correct design of mechanical installations, the type of equipment used, and their location. Internal hospital procedures and regulations can also have a major impact on the intensity of internal noise sources. Recently, new approaches to soundscape design, in addition to landscape, have been seriously considered in the design of health centers.

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