ACOUSTIC LANDSCAPE IN HOSPITALS

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MASTER'S DISSERTATION

ACOUSTIC LANDSCAPE IN HOSPITALS

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Abstract

Keywords: Room acoustics, sound environment, sound environment in hospitals, Odeon, absorption, reverberation time, speech clarity.

Our hospitals are full of sounds that are perceived as annoying and disruptive. Sound is generated from machines, alarms, ventilation systems, pagers and medical equipment. Hard, easy to clean surfaces that often are used in this type of premises also contribute to the problem. This affects patients, visitors and health professionals. A publication from WHO show that sound levels in hospitals have been rising consistently since the 1960's. The maximum value recommended by WHO for L_{eq} in patients' room is 35 dBA. Studies that have been done after this publication show that these recommendations are not even close to be fulfilled. A noisy and stressed environment may prevent our sick and weak patients to recover as they should. Knowledge is needed on how to design and plan our future hospital facilities in order reach the idealistic acoustical environment.

The purpose of the thesis is to provide a deeper insight in why acoustics matters in healthcare environments. Further, the purpose is to establish how an optimal sound environment can be achieved, from a room acoustical point of view. This is done through a case study, with measurements, interviews and room acoustic software. A method of how to design and plan rooms in healthcare environments is also developed. The main focus will be on room acoustics, other aspects that affect the sound environment will not be investigated.

Exposure of high sound levels may lead to decreased wellbeing for patients and medical personnel. The healing processes for patients become longer and personnel feel stressed and have a harder time performing mentally challenging work. The patient safety is at risk in an environment with high background noise, where it is hard to perceive spoken messages.

The case study of the thesis investigates SPL, reverberation time, clarity and STI. Measurements state that the SPL exceeds the recommendations from WHO with at the most 18 dBA. After evaluation it can be seen the sound levels are generally high in the room, with values up to 53 dBA.

According to interviews the investigated room is experienced as the calmest and quietest on the clinic. The most annoying and negative sound sources are noise from the corridors and patients talking or complaining.

The clarity and STI are evaluated through modelling. By making a suggestion of a new design clarity is improved by 6-8 dB for frequencies 250-8000 Hz and STI increases with 4 percentage points There is also a slightly improvement of reverberation time. The new design suggestion consists of wall panels that are added to parallel walls and to one single wall. Patients' beds are also screened by curtains.

Through discussion of case study and literature review suggestion of a design method is developed. Key steps in this method suggest that it is important to establish and decide the usage of the room. In this way an estimation of sound sources and the conditions of patients can be done. Declaration of certain acoustical requirements, for example clarity and STI, are recommended. Furthermore, creating an acoustical design team with architects, acousticians and personnel from the concerned hospital or clinic, is recommended.

Ljudmiljön i vårdlokaler
-Fallstudie av rumsakustik i ett patientrum

Genom att följa framtagna råd och riktlinjer vid ny-, till- eller ombyggnad av vårdlokaler kan en bättre ljudmiljö uppnås i vårdlokaler och på sjukhus.

Riktlinjer och råd för att uppnå en god ljudmiljö i vårdlokaler har utvecklats i ett examensarbete på Lunds Tekniska Högskola, i samarbete med ÅF Ljud och Vibrationer. En god ljudmiljö i vårdlokaler bidrar till minskad stress för personal och patienter. En lugn ljudmiljö är även positivt för patientsäkerheten, tillfriskningen och arbetsmiljön. Syftet med examensarbetet var ta fram råd som kan följas vid ny-, till- eller ombyggnad av rum i sjukhuslokaler.

Arbetet bestod av en fallstudie av ett patientrum på Skånes Universitetssjukhus i Lund. Studien innehöll mätningar, intervjuer med vårdpersonal och modellering i en rumsakustisk programvara.

Ljud och buller är ett vanligt inslag i dagens vårdlokaler och på sjukhus. Alarm, personsökare, maskiner, rullvagnar och medicinsk utrustning är några exempel på vanligt förekommande ljudkällor. Enligt rapporten ”Guidelines for community noise” som publicerades 1999 av WHO så har ljudnivån i hälso- och sjukvårdslokaler ökat konstant sedan 60-talet. Den rekommenderade ljudnivån (SPL) på 35 dBA överstigs enligt WHO i flertalet genomförda undersökningar.

Efterklangstid (T_{30}) är centralt för hur akustiken upplevs och mäter vilken tid det tar för ljudet att klinga av i ett rum. Speech Transmission Index (STI) mäter kvaliteten på talöverföring från talare till lyssnare. Taluppfattbarhet (C_{80}) mäter effekten av tidiga ljudreflektioner i ett rum. Dessa två mått är viktiga för hur lätt tal går att uppfatta ett rum. Det är särskilt viktigt med tydlighet och talöverföring i vårdlokaler, då meddelanden behöver kunna överföras utan problem och missuppfattningar.

T_{30} och SPL mättes i det utvalda patientrummet, vilka olika ljudkällor som fanns i rummet identifierades även. Vid utvärdering visade det sig att ljudnivåerna överskred rekommendationerna från WHO med som mest 18 dBA.

Intervjuer med personal som brukar vistas i patientrummet genomfördes även. Frågorna handlade om hur ljudmiljön i rummet upplevs och hur patienter och personal påverkas av ljudmiljön. Utvärdering av intervjuerna visade att personalen tyckte att ljudmiljön var okej i rummet, trots de höga ljudnivåerna som tidigare uppmätts. Personalen ansåg att ljudmiljön var betydligt sämre i andra rum på avdelningen. De vanligaste ljudkällorna ansågs vara ljud från korridoren utanför rummet, ljud från sängar och madrasser samt patienter eller personal som pratar.

Genom att modellera rummet med hjälp av en rumsakustisk programvara så undersöktes STI och C_{80}. En alternativ design för rummet togs även fram. Extra absorbenter adderades på väggarna och ett tjockare tyg användes som avskiljare mellan patientsängarna. På detta sätt så förbättrades STI och C_{80}, absorbenterna i rummet gör även framförallt att de höga ljudnivåerna kan skärmas av och absorberas.

Genom vidare analys och diskussion i arbetet så utvecklades riktlinjerna och råden som är tänka att användas som stöd vid ny-, till- eller ombyggnad av sjukhuslokaler för att uppnå en bättre ljudmiljö. Dessa punkter bidrar till att en god ljudmiljö kan uppnås och genom att följa stegen så sätts akustiken i fokus redan från början av projekten. Följande punkter listades i examensarbetets slutsats:

▪ **Akustiskt arbetsteam**. Skapa ett arbetsteam med fokus på akustik och ljudmiljö. Teamet kan bestå av akustiker, arkitekter, sjukhuspersonal och designers. Genom diskussioner, kunskapstillföring och workshops tidigt i projektet så får ljudmiljön och rumsakustiken erfordrad uppmärksamhet. Teamet är tänkt att fungera som ett stöd och support under hela byggprocessen och i projekt.

▪ **Specificera ljudkrav**. Lista ljudkrav och akustiska önskemål tidigt i projektet. Ljudkraven kan exempelvis innefatta parametrarna C_{80}, STI eller särskilda önskemål om T_{30} eller ljudnivåer.

▪ **Användning av rummet**. Fastställ vad rummet kommer användas till. Detta är centralt för vilken typ av patienter och utrustning som kommer finnas i rummet. Vilken beläggning och omsättning av patienter som rummet beräknas ha spelar även roll för ljudmiljön, då mycket rörelse bidrar till mer ljud och buller.

▪ **Patienter**. Bestäm vilken kategori av patienter som kommer vistas i rummet. Saker som har betydelse är patienternas tillstånd och för hur lång tid de beräknas vara inlagda. Särskilda patientgrupper, som exempelvis spädbarn är mer känsliga för buller än andra.

▪ **Identifiera ljudkällor**. Genom att ta reda på vilken typ av utrustning som kommer att behövas och användas i rummet, så kan potentiella ljudkällor identifieras. Dessa källor kan sedan skärmas av, anpassas eller placeras så att de blir så tysta som krävs.

▪ **Absorptionsmaterial**. Använd absorptionsmaterial som är anpassat efter de krav på hygien och rengöring som finns i vårdlokaler.

▪ **Placering av absorbenter**. Absorbenter kan exempelvis placeras i taket eller på väggar. Avskiljande tygstycken kan också användas. Placera väggabsorbenter i höjd med patienternas huvud och på parallella ytor. Skärmar kan även till exempel placeras framför maskiner för att avskärma från ljud.

▪ **BBR:s krav**. Ha som mål att uppfylla en hög ljudklass enligt BBR. Att den högsta ljudklassen är uppfylld ger emellertid inga garantier för att ljudmiljön blir tillfredsställande eller som önskat, om de andra stegen inte prioriteras.

Acknowledgments

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I want to thank my supervisor Delphine Bard for all the support and encouragement through this semester. Thanks to Kristian Stålne for feedback and rewarding discussion.

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2014-06-05, Lund

Mia Lindros

List of terms

P_{ref}	(Pa)	Reference pressure, $2 \cdot 10^{-5}$ Pa
T_{30}, T_{20}	(s)	Reverberation time
L_p	(dB)	Sound pressure level
SPL	(dB)	Sound pressure level
L_{eq}	(dB)	Equivalent sound pressure level
L_{pA}	(dBA)	A-weighted SPL
L_{pC}	(dBC)	C-weighted SPL
c	(m/s)	The propagation velocity of sound in air (20 ℃)), 343,4 m/s
λ	(m)	Wavelength
f	(Hz)	Frequency
α	(-)	Sound absorption coefficient
STI	(-)	Speech transmission index
C_{80}, C_{50}	(dB)	Speech clarity

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1 Introduction

1.1 Background

Humans today are daily exposed to noise and vibrations, which can lead to increased stress and poor health. One vulnerable part of the society that is particularly exposed is our hospitals. In the hospital we keep and care for our frail and sick individuals. That is why the health care environment has to be a place where people can recover, sleep, relax and get well.

Today's hospitals are full of sound that is perceived as annoying and disruptive. Sound is generated from machines, alarms, ventilation systems and people in constant movement. The surfaces in hospital facilities, which often are hard since they have to be easy to clean, also contribute to the problem. Social cuts have also led to a lack of space and that patients sometimes have to share rooms that originally was designed for fewer persons. The sound environment affects patients, visitors and health professionals. The noisy and stressed environment may prevent our sick and weak patients to recover as they should. Knowledge is needed on how to design and plan our future hospital facilities in order to reach the idealistic acoustical environment.

To meet new demands there has been a focus on building new hospitals and rebuilding old healthcare buildings over the last years. Sustainability, environmental friendly and efficiency are often the key words in these types of projects. But questions can be raised about how sustainable it is to rebuild due to poor acoustical conditions.

1.2 Purpose

The purpose of the thesis is to provide a deeper insight in why acoustics matters in healthcare environments. Consequences that the sound environment may have on patients and medical staff will be investigated. Moreover, how the design of spaces in hospitals is influenced by regulations and standards is studied.

Furthermore, the purpose is to find out how an optimal sound environment can be achieved, from a room acoustical point of view. This is done through an interaction between literature review, measurements, interviews and the use of room acoustic software. This methodology is chosen since it will give a complete and wide representation of how a better sound environment may be achieved. The interactive method takes on many aspects, both objective and hard facts, which affect the results of how to design and plan hospital rooms in different ways. The room acoustical parameters reverberation time, clarity, speech transmission index and sound pressure level are investigated and looked into.

Through analysis and outcome of the results, a set of guidelines of how to design rooms in healthcare environments will be developed.

1.3 Scope and limitations

There are many aspects that can affect patients and personnel in hospitals, such as lightning, temperature and air quality. This report only focus on sound and the acoustical part. The thesis will only cover the acoustical environment in a patient room, therefore the results will not be valid for all types of spaces that exist in hospitals. Other room types that exist are for example emergency rooms, operation rooms, corridors and waiting room. The developed method of how to design and plan a patient room will be adjusted according to how ÅF works in the process of room acoustic design. The main focus in the thesis will be on room acoustics, other aspects that affect the sound environment in a room, such as sound insulation or traffic noise, will not be investigated.

1.4 Outline

The thesis is divided into chapters 2-11 with the following content:

Chapter 2 describes the motivation behind the thesis.

Chapter 3 describes the methods that are used.

Chapter 4 is a theoretical section that includes an introduction to acoustical terms and definitions, with focus on room acoustics.

Chapter 5 contains information about practical evaluation of room acoustics. The design of the case study is also stated and motivated. Further on, the chapter describes the Swedish standards and building regulation that concern spaces in hospitals.

Chapter 6 describes the measurements that are performed. The chapter also contains results from the measurements and results from the ocular inspection. The SPL and the reverberation time is measured.

Chapter 7 includes a summary and an evaluation of interviews performed with staff from the hospital.

Chapter 8 contains information about the modelling phase; an outcome of the modelling is presented with an original design together with a suggestion of a new design. The reverberation time, speech clarity and the speech transmission index are simulated.

Chapter 9 contains discussions of the literature study and the case study.

Chapter 10 contains a suggestion of design method that is supposed to be a support when designing the acoustical environment in hospitals.

Chapter 11 consists of the conclusion and further work that is to be done.

2 Motivation of thesis

This chapter includes an informative motivation to the importance of acoustics in hospitals. It describes the effects that noise and sound have on humans and the impacts that sound has on patients and staff. The underlying factors for why the topic is interesting and important are described in the motivation.

2.1 Noise effects on humans

Effects of noise exposure are complex and could mean anything from a physical damage of the hearing organs to secondary reactions after human interpretation of the sound [1]. The effects of noise can be evaluated in many ways. One way is to divide the effects into hearing damage, masking effects and non-auditory damages [2].

2.1.1 Hearing damage

Noise can cause damage to the nerve cells of the inner ear. One powerful impulse signal at a high frequency is enough to forever destroy the human hearing. The beginning of a hearing damage usually occurs in the frequency range of 4000-6000 Hz, see Figure 1 [2].

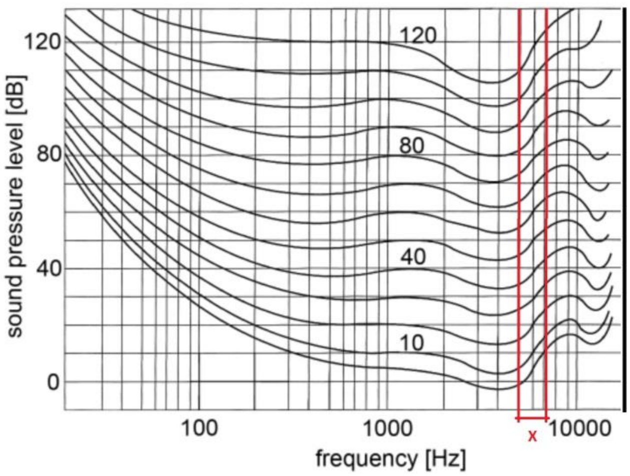

Figure 1. The X marks out the frequency area where hearing damages usually occur [3].

A damage that has come from staying in a noisy environment can sometimes be temporary, and normal hearing may return after a few hours up to one day. A hearing loss that remains after a couple of days is unfortunately often a permanent damage. Continued daily exposure increases the damage and can also lead to degraded speech intelligibility [2]. A hearing damage can be followed by tinnitus, a constant ringing tone in the ears. The symptom with a constant present sound is often experienced as very distressing and frustrating [1]. See Figure 2 for an illustration of damaged and healthy hearing cells.

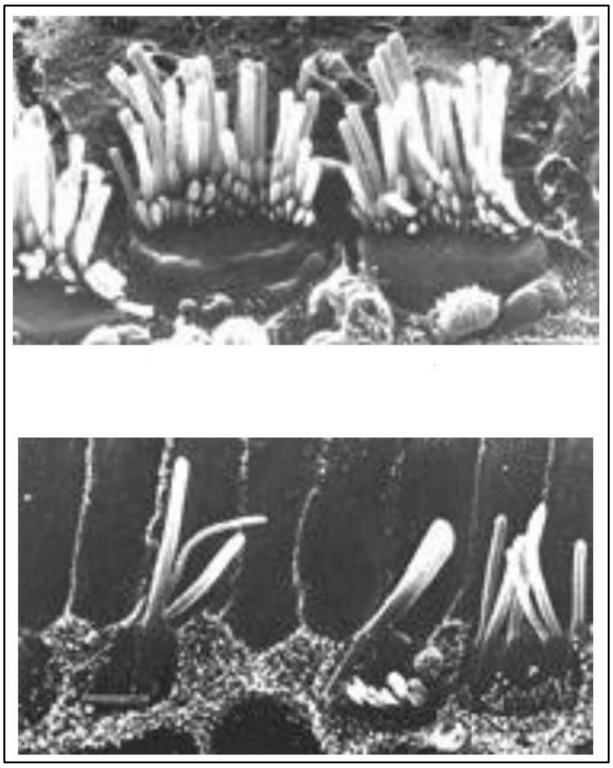

Figure 2. This figure shows healthy hearing cells at the top and damaged hearing cells at the bottom [3].

2.1.2 Masking effects, annoyance and distraction

Noise is also distracting for the concentration and can be aggravating, annoying and tiring. Noise affects the intelligibility of speech when the noise level exceeds the speech, this is known as masking [1]. Masking means that a sound gets masked and lost due to other sounds, for example background noise. Noise can for example mask sound from a warning alarm, which leads to an increased risk for accidents [2]. Masking can cause misunderstanding and that important information is missed out. Long reverberation time in combination with noise degrades speech intelligibility even further [1].

It is well known that noise in general reduces work capacity. Even if a human is not knowingly annoyed by a constant high level of background noise, the body is dangerously affected [2]. Noise can cause negative effects on performance and learning, since the ability to understand speech and to concentrate is disturbed. Effects of noise on work performance become more severe the longer the work is performed in a loud environment. More effort on the concentration may help temporarily, but ultimately it can result in human impacts like exhaustion and concentration difficulties [1]. Background noise that makes an assignment more difficult and tiring, further contributes to higher levels of stress [4].

Sleep is central to human well-being and health. Disturbance of sleep is therefore one of the most serious effects of noise exposure. Vulnerable groups, such as old and sick are at higher risk of suffering from sleeping disturbance as a result of noise. [1]. Noise and sound obviously affect people's ability to rest and sleep. Both constant background noise and single peaks of sound affects the depth of sleep in a negative way [2].

Distraction is clearly one negative effect of noise [4]. Persistent background noise is tiring and exhausting when mentally challenging work is to be performed. It is mainly high-frequent noise and intermittent sound sources that disturb the human concentration [2]. Moreover, there are things that make sound more distracting, for example sudden changes of the sound, especially at high sound levels. Another factor is the content of information, where the human speech is central. This since it is harder for humans not to listen to and register irrelevant talk, in comparison with a single tone that does not contain any information and is therefore easier to ignore [4].

2.1.3 Mental illness, psychosocial and medical effects

Noise may alone, or in combination with other stress factors cause different kinds of psychosocial effects or symptoms. Aggressive reactions may for example occur when individuals are not able to control high sound levels [1]. Noise is not believed to directly cause mental illness. It is however assumed to intensify and accelerate the development of latent mental disorders. Studies on the harmful effects of noise on mental health have shown symptoms as emotional stress, anxiety, nervous complaints and changes in mood. Moreover, large-scale population studies have shown results of associations between noise exposure and a variety of mental health indicators, including the intake of psychotropic drugs and the consumption of sleeping pills [5].

Besides the psychosocial effects, there is concern about the impact of noise on public health, particularly regarding cardiovascular effects [6]. Furthermore, high sound levels can have an impact on many other functions in the human body, for example respiration and digestion [2].

It has been observed that sudden or high sound levels could cause a temporary rise of heart frequency and blood pressure. Exposure to very high sound levels over a longer time has been proven to cause permanent high blood pressure [1]. Severe noise exposure activates the hormonal and autonomic systems, which may lead to temporary changes, such as increased heart rate and vasoconstriction. If the exposure gets persistent, permanent side effects like hypertension and ischaemic heart disease may occur [5].

Animal tests have shown that high noise levels (>90 dBA) affect the function of the adrenal gland and the hypophysis. The human blood composition may change due to sound levels above 100 dBA [2].

2.1.4 Vulnerable groups

Protective standards are mostly derived from observations or studies on the health effects of noise on normal or average groups of people. Vulnerable groups are often underrepresented in these studies. People with decreased personal abilities, people with medical problems or particular diseases, people who have hearing impairment or who are blind, babies, children and elderly are examples of groups that are vulnerable. These individuals may be less capable to cope with the impacts of noise exposure and may also be at a greater risk for harmful effects [5].

2.2 Acoustics in hospitals

The significance of the sound environment in hospitals for an effective healing process of patients has been shown in earlier research. The healthcare industry has for a long time been characterized by insufficient funds, facilities and staff. This in combination with heavy work load, has led to stress that affects patients' recovery and well-being [7].

The sound environment in hospital is a complex topic to study. When analysing this type of sound environment it is important to keep in mind that each space is unique and special and that many properties therefore will vary. Things that will differ from case to case are for example the condition of patients, level of occupancy, numbers of visitors, machines, the work environment ant the architectural design [8]. Because of this, the sound sources are different depending on what type of care unit that is being studied.

In 2010 the study "Noise pollution and its effects on medical care workers and patients" was performed. This study describes among other factors some of the most common sound sources in healthcare environments. These are for instance alarms, paging systems, medical equipment, portable carts, staff activities and high load ventilation, heating and air-conditioning systems. Surfaces also contribute to the noisy environment, as they often are hard and reflective, since they have to be easy to clean [8].

Healthcare providers' awareness for the acoustical climate in hospitals has been raised as they have faced strong pressures to reduce costs yet increase the quality of care. An aging population in combination with technical lagging and old hospital buildings are the reasons why many countries now need to renovate their hospitals and build new ones. Some countries, including Britain and the United States, have initiated and implemented vast programs of healthcare building construction [9].

Among the previous research that has been done, the World Health Organization (WHO) published a set of guidelines and recommended hospital noise levels in 1999. The maximum value recommended by WHO for L_{eq} in patients' room is 35 dBA. This investigation showed that sound levels in hospitals have been rising consistently since the 1960's. Studies that have been done after the publications of the guidelines show that these recommendations are not even close to be fulfilled [10].

Previous research has shown that it is not only the noise level that effects the sound environment in the hospitals, other acoustic parameters for example STI and clarity, also have an important role. The parameters may affect medical staffs' performance and the speech intelligibility between patients, visitors and staff [11].

2.2.1 The impact of sound on patients

Noise affects people negative in both a physiologically and psychologically way. As mention earlier, being exposed to noise can lead to a number of side effects. For example increased stress, hearing loss, problems with heart and blood vessels and weakening of the immune system [11]. The need for acoustical comfort in hospital is central in the recovering process of a patient. The sound environment affects the quality of sleep and the patient's ability to relax [11].

The study "Acoustic Analysis of High Care Unit (HCU) at Hospital "X" in Bandung, Indonesia", published in 2011, investigated three acoustical parameters in a High Care Unit (HCU). Speech clarity, sound pressure level and reverberation time were investigated through measurements, simulations with acoustical software and subjective observations. Through subjective observation, the study showed that noise in the unit was dominated by sources from communication. Furthermore, the most disturbing factor came from alarms, with a frequency range between 630 Hz and 2000 Hz. The results of the study showed, through simulations, that coating concrete walls with fiberglass board, gave an increase in of the speech clarity, as well as a decrease in both reverberation time and SPL [11].

2.2.2 The impact of sound on hospital staff

As mentioned earlier, noise has a negative interfering and distracting effect on humans' performance at work. The acoustical comfort is important to the working environment as well, where too much noise leads to stressed, tired and distracted staff. The working quality of the medical staff is also affected by the sound environment, as they have to be able to concentrate fully on their work due to the patient safety [11].

Earlier studies show that a noisy work environment may decrease short-term memory and mental efficiency of the staff. High levels of hospital noise can also lead to exhaustion and hearing loss among the staff. An increased sound absorption can be correlated to improvement in the staff perception of noise and psychosocial situation. The sound environment's impact on the hospital staff can also be a security risk for the patients as well, in terms of speech interference and increased medical errors [10].

In the article "Acoustics and psychosocial environment in intensive coronary care", published in 2005, the influence of different acoustic conditions on the work environment and the staff in a coronary critical care unit was examined. Reverberation times and speech intelligibility was improved during the study, with a change from sound reflecting tiles to sound absorbing tiles with an identical appearance. The results of the article showed that improved acoustics positively affect the work environment. Staff that had the afternoon shift experienced significantly lower work demands and reported less pressure and strain, after the improved design [9].

3 Method

This chapter describes the methods that are used in the different part of the thesis. The thesis consists of a number of stages that has been decided through discussions and consultation with supervisors and consultants within the acoustical field. Briefly, the thesis mainly consists of a literature study and a case study. The case study includes measurements, interviews and modelling. Finally, a method of how to design patient rooms in hospitals is established through discussion and analysis of the work that have been performed in the thesis.

3.1 Research methods

The thesis consists of both qualitative and quantitative methods. Below follows a description of the two research methods.

3.1.1 Qualitative method

Qualitative research method aims to investigate how humans are experiencing and perceiving the topic of the thesis. The method is used when the subject consists of something that is not measurable. Understanding and insight are often the main goals of the research [12]. The qualitative work in the thesis consists of interviews, where human opinions and impressions of the sound environment are investigated and evaluated.

3.1.2 Quantitative method

A quantitative method often consists of collecting facts and studying the relationships between different sets of facts. The investigated topic is measurable and the result can often be presented with figures or statistics [12]. The quantitative work in the thesis consists of measurements and modelling, where the results are measureable and presented with figures.

3.2 Validity and reliability

To assure the credibility of the thesis, a description of validity and reliability is explained in this section. Several things contribute to the validity and reliability of the thesis. For instance, a variety of different sources are used for the literature review. Furthermore, calibrated and approved equipment are used during the measurements.

3.2.1 Internal validity

Internal validity is about the extent to which the results of the thesis are consistent with the reality. Results should reflect the reality and the researcher should also be aware of what parameters that really are being measured [13]. Internal validity of the thesis is achieved with the method that consists of both measurements, modelling and interviews. In this way a wide range of parameters that effect the sound environment in a room are investigated.

3.2.2 External validity

External validity means to what extent the results from the thesis are generalizable. Moreover, if it is possible to apply the results in other studies or cases [13]. The results could be used for the same type of room that is investigated in the thesis, at other hospitals or clinics.

3.2.3 Reliability

Reliability refers to the repeatability or consistency of the research measures. High level of reliability means that someone else is able to repeat the same experiment and still end up with the same results [13]. Reliability is partly ensured through the methods of the thesis, which are well described, defined and explained. It would be possible to repeat the thesis, but the results would probably end up being slightly different. The result of an acoustical measurement very much depend on the conditions that existed during the experiment.

3.3 Literature study

To get data and information on the different subjects of interest, a literature study is carried out. This provides necessary background information to the thesis and is an important part of the work process and gives a deeper understanding of the subject. The outline consists of a motivation of the thesis and a theory chapter about room acoustics.

The motivation of the thesis is described in the previous chapter and consists of information about the importance of acoustics in hospitals. It also describes the effects that noise and sound have on humans. The information for the part about acoustics in hospitals is obtained from databases via Lund University libraries. A summary from a symposium arranged by the Sound Environment Centre at Lund University is used as well as other articles and studies that had been done on the subject. Information regarding the effects of noise and sound on humans was collected from books.

The theory chapter is an introduction to acoustical terms and definitions. The information is mainly collected from literature, but also from the internet and companies within the acoustical field and manufacturers of acoustical building materials.

3.4 Evaluation of room acoustics

A review of how to perform and evaluate measurements of room acoustical parameters is done. This in order to prepare for the case study and identify which parameters that are relevant to study and measure. ISO 3382, which contains information about measurements of room acoustic parameters, is studied. ISO 3382-1 is for performance spaces, such as auditoriums and ISO 3382-2 applies to ordinary rooms.

3.4.1 Design of case study

A design of the case study is done using information from the motivation, literature review and from the study of how to perform and evaluate measurements of room acoustical parameters. Motivation of why the parameters are studied is stated in this section. The parameters and the design of the case study are also chosen in consultation with supervisors.

The following acoustical parameters are evaluated through the case study, either with measurements or modelling.

- Reverberation time
- Clarity
- SPL
- STI

3.4.2 Swedish standards and building regulations

Swedish standards and building regulation are studied in order to make the intended measurements and results as accurate as possible. The standards are needed in order to make an evaluation and analysis of the result from the measurements.

The sections that are covered are sound classifications in BBR, sound classifications of spaces in buildings and measurements of room acoustic parameters. Information is primarily collected from the standards, but also from literature.

3.5 A case study: Patient room at orthopaedics department

To get a picture of the actual situation in today's hospitals and to get a sense of reality, a case study of a patient room is performed. The orthopaedics department is selected in consultation with supervisors and responsible personnel at Skåne University Hospital in Lund. Access to an appropriate room is given by the head of the orthopaedics department. The room is selected in order not to disturb the activities in the hospital and based on what is best for the patients, both regarding integrity and health.

3.5.1 Methods of a case study

The purpose of a case study is to investigate a small part of a large system. The reality is described and represented with help of a case study. One single case can never fully represent the actual reality, this is one problem that comes with a case study. Furthermore, the conclusions that can be drawn from a case study can be interpreted as indications of the reality [14].

3.5.2 Measurements and ocular inspection

Sound pressure level and reverberation time are evaluated from the case study through measurements.

The measurements are done in a four-bed room on the orthopaedic department as mentioned in the previous section. The sound pressure level is measured in a number of suitable positions. Background noise from medical equipment, ventilation systems and other sources is identified, measured and recorded. Recordings are done to create a picture of how a patient could experience the sound environment during a stay at the hospital later on in the thesis.

Reverberation time is measured and analysed. The measurements are done according to the standards SS-EN ISO 3382-2:2008 and SS 025263.

3.5.3 Ocular inspection

An ocular investigation of the room is done onsite, this in order to identify noise sources and to get an understanding of how the room is built. Surfaces, dimensions, materials and other significant parameters in the room are investigated. This information is needed further on in the thesis, when modelling and evaluation are to be done.

3.5.4 Interviews

Shorter interviews with the staff concerned are performed as a complement to the measurements. This provides a human reflection and opinion of how the sound environment in the room is experienced. The interviews also contribute with some general opinions and thoughts on acoustics in hospitals.

The method in this case consists of oral interviews that are recorded and later transcribed. The interviews will be like an open discussion, which takes on four basic questions about the acoustical climate in the specific room. The evaluation of the interviews is the main part of the interview chapter and the questions can be found in appendix II. The interviews can be described as a combination of semi-structured interviews and open interviews. The questions are designed to create further discussions during the interviews.

3.5.5 Modelling, Odeon software

By using the room acoustic software Odeon, simulations of the interior acoustics of the room can be done. The modelling is done to be able to evaluate supplementary acoustical parameters. Clarity and Speech Transmission Index are evaluated through simulations in the program. This is done as a compliment to the measurements, as well as to present eventual improvements of the design.

The properties of the room can be changed to get the optimal acoustical environment that is desired and needed. An alternative for how the room could be designed when it comes to surfaces, ceilings, sound isolation and similar will be presented. Suggestions for improvement are developed, this is done through simulations in the program. Different types of material are tested to get an as optimal solution as possible.

Sources of error

Sources of errors may eventually lead to unwanted and unreasonable results. Common sources of error in room acoustical simulations with Odeon are listed below [15].

- The approximations made in the Odeon calculation algorithms.
- Inappropriate calculation parameters.
- Imprecise material/absorption coefficients.
- Imprecise material/scattering coefficients.
- Geometry definition may not be accurate.
- The measured reference data to which simulations are compared may not be accurate [15].

3.6 Analysis and discussion

The outcomes of the measurements, interviews and the modelling are analysed and discussed. Information, opinions and facts that previously have been taken on in the report are analysed. From this discussion a set of guidelines is formulated. This guidance will work as support when to design or improve the sound environment in hospital rooms.

4 An introduction to acoustical terms and definitions

The literature study forms the basis of this theory section. The chapter has focus on introducing acoustical terms and definitions, with the main focus on room acoustics. The acoustic area is studied to increase the understanding of the subject and for the further work that is to come. The theory section is also a necessary foundation for the analysis and discussion part.

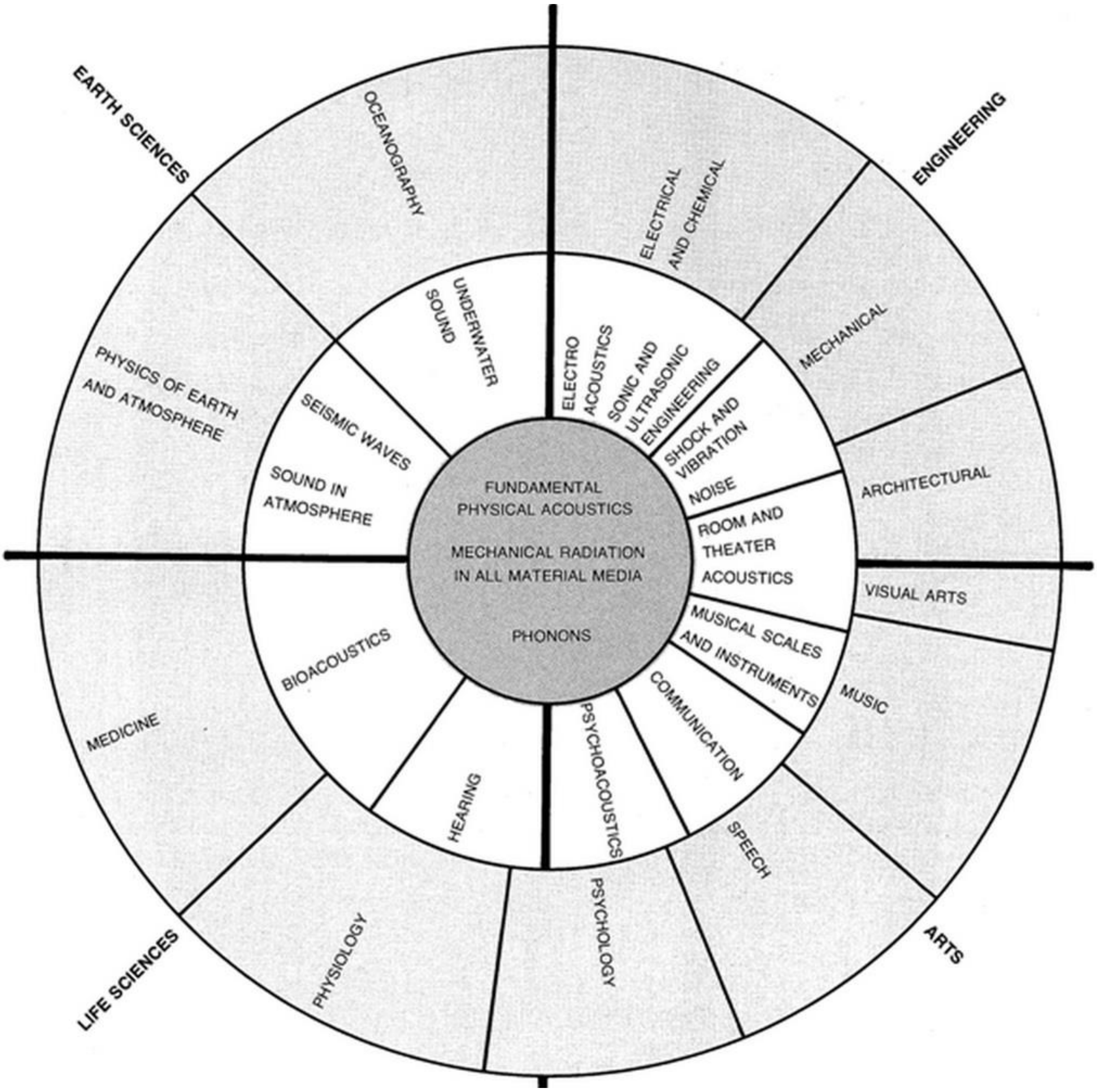

Figure 3. Lindsay's wheel of acoustics [16].

Figure 3 is an overview of the broad field of study that acoustics actually consists of. The circle is called Lindsay's wheel of acoustics and shows that the acoustics involves everything from mechanics to psychology and arts. It is important to have this wheel in mind when working with acoustics, even from an engineering point of view [16].

4.1 Sound pressure level

Sound is a pressure wave that propagates through a media, for example air or water. Oscillating particles create a pressure wave that is transported through the media. The wave movements in the air consist of periodic pressure differences above and below the atmospheric pressure. When sound waves reach the human ear, the eardrum is set in motion and starts to create vibrations. Through the mechanisms of the ear, the vibrations are converted into nerve signals that are sent to the brain and perceived by us as sound [1].

The strength of a sound wave can be described with a root mean square relationship, which is calculated according to equation (1).

$$\tilde{p} = \sqrt{\frac{1}{\Delta t}\int_{t_0}^{t_0+\Delta_t} p^2(t)\,dt} \qquad (1)$$

The range of the pressure differences that humans can distinguish is very wide, this means that it is not possible to present sound pressure on a linear scale. For this reason sound pressure level, SPL, is used. Sound pressure level is a logarithmic measure specified in decibels and is used to quantify noise. SPL is calculated as equation (2), where P_{ref} is a reference pressure for airborne sound with a value of $2 \cdot 10^{-5}$ Pa [1].

$$L_p = 10\log\left(\frac{\tilde{p}^2}{p_{ref}^2}\right) \qquad (2)$$

The equivalent SPL, $L_{eq,T}$ is the value of SPL over time [1]. $L_{eq,T}$ is calculated according to equation (3).

$$L_{eq,T} = 10\log\left(\frac{1}{T}\int_0^T \frac{p^2}{p_{ref}^2}\,dt\right) = 10\log\left(\frac{1}{T}\int_0^T 10^{L_p(t)/10}dt\right) \qquad (3)$$

Since SPL is a logarithmic measure it cannot be linearly added. Equation (4) is used when adding several sound sources. Consequently this means that when two sound sources with the same SPL is added, Lp increases with 3 dB [1].

$$L_{p,total} = 10\log\left(\sum_{n=1}^{n} 10^{L_p/10}\right) \qquad (4)$$

4.2 Frequency and wavelength

A sound wave can be described as a cosine or sine function. The distance between the two equal values of the function is referred to as a wavelength, λ (m) which can be seen in Figure 4. The time it takes for the sound to travel one wave length is called one period, T (s) [2].

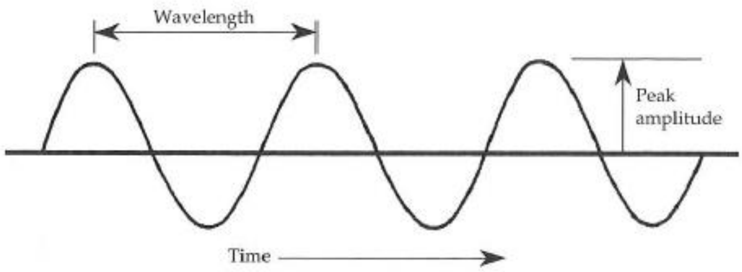

Figure 4. Wavelength is the distance a wave travels in the time it takes to complete one cycle. It can also be expressed as the distance from one point on a periodic wave to the corresponding point on the next cycle of the wave [19].

The number of waves that passes a given point during one second is called the frequency of the wave, f (Hz). The wavelength can be determined by the propagation velocity of sound, c (m/s), and the frequency according to equation (3) [1].

$$c = \lambda \cdot f \qquad (3)$$

4.3 Reverberation time

When a sound source in a room is switched off, the sound energy in the room decreases gradually. The rate of the decay depends on the geometry and the damping in the room. The time it takes for the sound to decay is called reverberation time and is measured in seconds. T_{60} is defined as the time it takes for the sound energy to reduce with 60 dB. Further on, T_{30} is the time it takes for the sound do reduce with 30 dB [1]. In this thesis the T_{30} is used for the reverberation time.

The sound decreases exponentially and therefore the time it takes for the sound to decay 60 dB is independent of the intensity of the sound source [1]. This exponential relationship is described with equation (3).

$$E(t) = E_0 \cdot e^{-t/\tau} \qquad (3)$$

The relationship between the reverberation time and the sound absorption in the room can be described with the following expression (4).

$$T_{60} = K \cdot \frac{V}{A} \qquad (4)$$

Where K is a constant with the value of 0,161 s/m and V is the volume of the room and A is the absorption area. This expression is called Sabine's formula [1].

The sound field in a room has to be similar to a diffused sound field for the formula to be valid; this means that the sound is equally spread across the volume of the room. A diffused sound field is characterized by sound pressure that decays exponentially when a sound source is turned off. The sound also decays when the incident waves hit walls, surfaces and furniture. The more absorbing surfaces and objects, the quicker the sound decays [1].

4.4 Absorption

When an incident sound wave hits an object or material one part of the wave gets reflected, one part gets absorbed. This can be described with equation (5), where Π_r is the reflected part, Π_a is the absorbed part and Π_i is the incident sound wave [17].

$$\Pi_i = \Pi_r + \Pi_a \qquad (5)$$

The absorbed part of energy from the sound wave can be divided into one part that is transmitted through the material and another part that can be described as converted energy [18]. This is illustrated through Figure 5, where 1 is the transmitted part, 2 is the converted part and 3 is the reflected part.

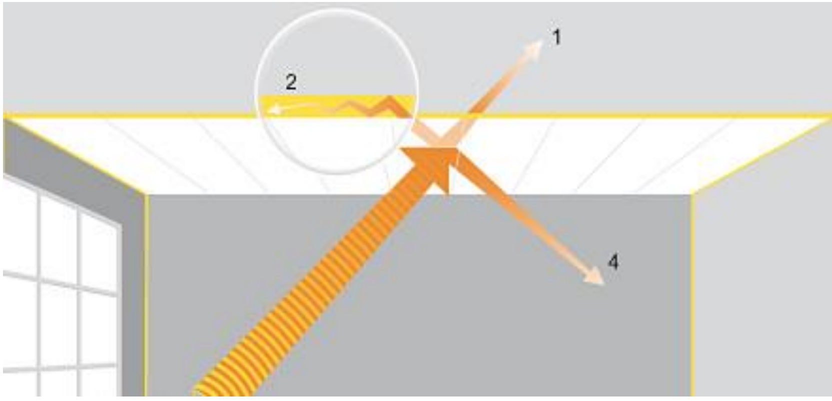

Figure 5. Illustration of absorption, transmission and reflection of a sound wave [18].

The sound absorbing properties of a material are expressed with the absorption coefficient, α, as a function of frequency where a value of 1 indicates total absorption and no reflection. An absorption coefficient is the ratio between the reflected sound effect and the total incident sound effect [17]. See equation (6).

$$\alpha = \frac{\Pi_r}{\Pi_i} \qquad (6)$$

The sound absorption area, A, provided by a particular material is obtained by multiplying its absorption coefficient by the surface area of the material that is exposed to sound.

$$A = \alpha \cdot S \qquad (7)$$

When calculating a room's total absorption all the materials in the room, according to their area, will contribute to the total absorption [19]. The total sound absorption in a room is obtained by equation (8).

$$A = \sum S_1\alpha_1 + S_2\alpha_2 + S_3\alpha_3 \ldots \qquad (8)$$

When measuring a material's effectiveness at absorbing sound a graph which describes the absorption at different frequencies is obtained, see Figure 6. The materials acoustical properties are described in absorption classes. The classes range from A to E, where A absorbs most and E at least [20].

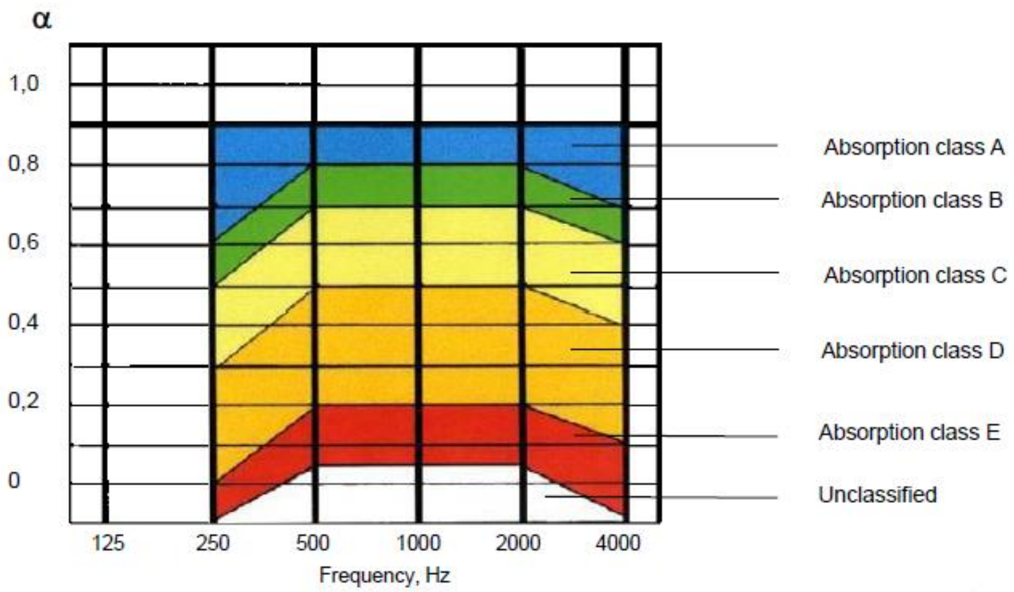

Figure 6. Absorption classes A to E [28].

4.4.1 Absorbers

When sound is absorbed, the sound energy is converted to other forms of energy. The sound energy is converted directly to heat energy by friction or through setting a structure in motion [1].

Porous absorbers

The sound loses energy when air molecules flow through pores or fibres. Friction occurs in the pores due to the viscosity of the air. Porous absorbers are effective for high frequencies. Examples of porous absorbers are mineral wool, curtains, wood fibre boards, felt and fabric. A disadvantage with porous absorbers is that they become impractically thick if they are to absorb in the lower frequencies [1].

Resonance absorbers

The principle of resonance absorbers is that sound waves set a resonance system in motion. The system must not be too heavy, since the air molecules have to be able to set it in motion. This type of absorber works best for absorption of resonance frequencies and is mostly used for absorption of sound with lower frequency [1].

4.5 Speech clarity

Speech clarity is about the quality of the human voice that is transmissioned to a listener. It is often difficult for people to understand each other in a room with hard surfaces and a lot of background noise [2]. If the speech transmission in a room is poor, it is difficult to perceive and notice variations in speech. Factors that reduce the speech intelligibility are for instance, background noise, long reverberation time and echoes [21].

The direct sound reaches the listeners ear first and is followed by early reflections. The early reflections have a positive effect on speech clarity if they reach the listener within 50 ms and thus become integrated with the direct sound [21]. This is illustrated below in Figure 7.

Figure 7. The direct sound is the black arrow and the reflections are illustrated with the grey arrows [21].

Reflections that come later may be disturbing and lead to that the speech is perceived less well. Clarity measurement, C_{50}, compares the sound energy in early sound reflexes with the later reflections. A high value of C_{50} is positive for the speech clarity, see Figure 8 [21].

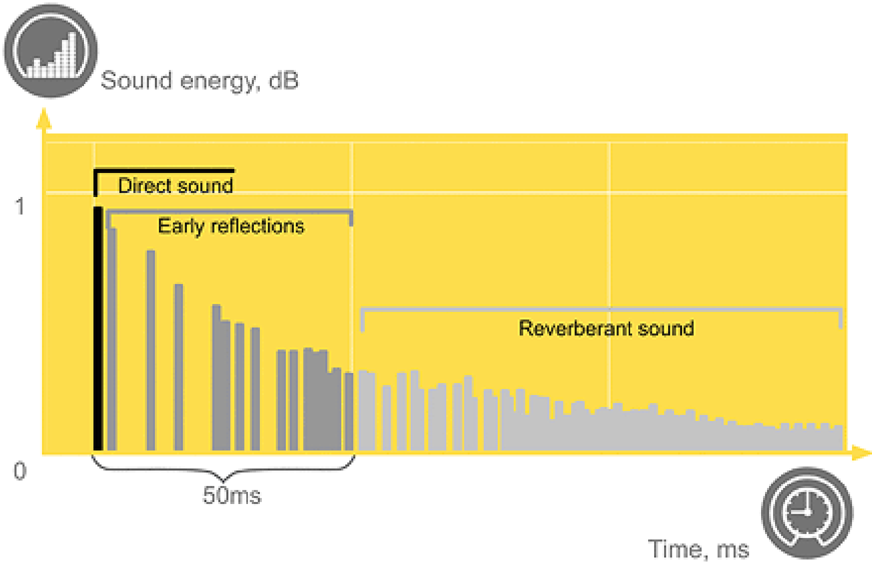

Figure 8. Illustration of direct sound, early reflections and reverberant sound in a graph [21].

Speech Transmission Index, STI, measures the quality of the speech that is transferred from the speaker to a listener. A high value of the STI is positive for the speech transmission. Variations in speech are perceived less well if the speech transmission is poor. As mentioned earlier, background noise, long reverberation time and echoes are factors that affect the speech transmission, these factors may also contribute to a lower STI [21]. See Table 1 for description of the STI scale.

Table 1. The subjective scale of STI index [15].

Subjective scale	STI value
Bad	0,00-0,30
Poor	0,30-0,45
Fair	0,45-0,60
Good	0,60-0,75
Excellent	0,75-1,00

4.6 The perception of sound

To match the human hearing SPL can be weighted through an A-filter. The weighting is supposed to represent the human hearing as it is experienced through the auditory organs [19]. The weighting is done as formula 9, where the weighting consists of one value for each frequency. Other common filters are B-filter and C-filter, see Figure 9 for the main differences.

$$L_w = 10\log\left(\sum 10^{(L_n + \text{weighting})/10}\right) \quad (9)$$

When the A-filter is used, the value is designated dBA. dBA readings are usually lower than unweighted values in dB. Frequency weightings such as the A-filter cannot accurately represent the human experience of loudness [19]. The A-filer is designed for lower sound levels, the B-filter is for medium-high levels and the C-filter is adjusted for high levels of sound [1].

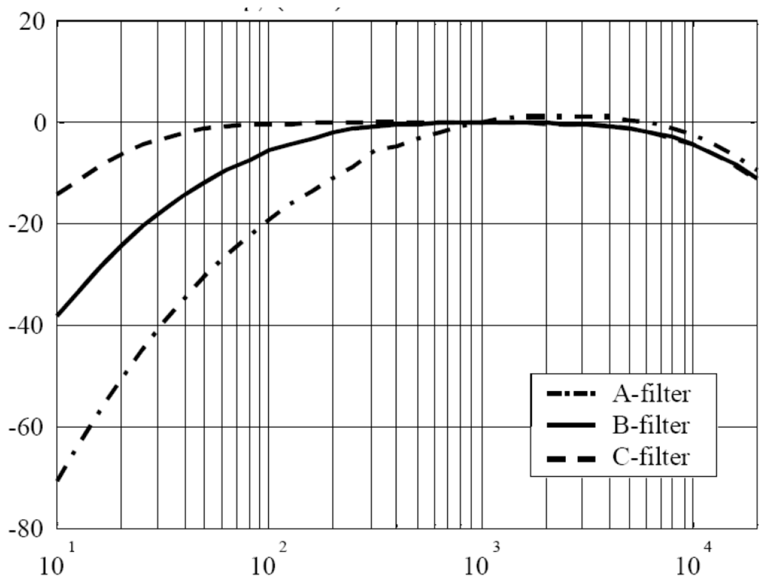

Figure 9. Difference between A, B and C filters, with the frequency (Hz) on the horizontal axis and the added weighting value (dB) on the vertical axis [1].

The sensitivity of the ear varies with frequency. A 100 Hz tone of 50 dB is subjectively not perceived as loud as a 1000 Hz tone of 50 dB [1]. Loudness is a subjective term and is not the same as a SPL reading.

Figure 10 shows that perceived loudness varies with frequency and SPL. Equal-loudness contours of the human ear for pure tones are shown in the figure. Inverting the curves gives the frequency response of the ear in terms of loudness level [19]. As the figure shows, frequency dependency of the ear is more distinct at lower sound levels [1].

Frequency analysis of the human speech shows that vowels mainly are in the frequency range of 300-3000 Hz. Toned consonants, for example n and v, are in the range of 300-4000 Hz and voiceless consonants are in 2500-12000 Hz. Most of the linguistic information in speech lies within the consonants [1].

What is experienced as good room acoustics by humans depends on various factors, such as the usage of the room, size of the room, expectations of the sound environment and comparison with other similar rooms [2].

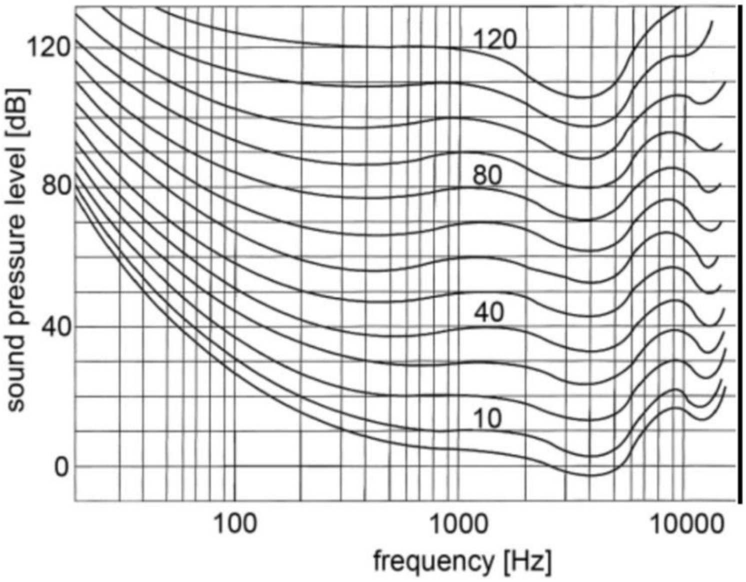

Figure 10. Equal-loudness contours of the human ear. The contours reveal the lack of sensitivity of the ear to bass tones, especially at lower sound levels [3].

5 Evaluation of room acoustics

This chapter contains information about measurements of room acoustical parameters, along with the associated standards and building regulations that exist today. The acoustical parameters that further are evaluated in the case study are described and motivated. Sound classifications in BBR and sound classifications of spaces in buildings are also described in this chapter.

5.1 Measurements of room acoustical parameters

The ISO 3382 comprises measurements of room acoustic parameters; ISO 3382-1 is for performance spaces, such as auditoriums and ISO 3382-2 apply to ordinary rooms.

There are many reasons why to measure the reverberation time in a room. Reverberation time affects the intelligibility of speech, the sound pressure level from noise sources and the perception of privacy in a room. The reverberation time may also be measured to determine the correction term for room absorption that is used in many acoustic measurements, for example measurement of sound insulation [22].

The reverberation is significant for the acoustical qualities of a room. Agreement has been made about that other parameters sometimes also are needed when an acoustical evaluation of a room is to be done [23]. When designing auditoriums, concert halls or other buildings with high demands on the acoustics, it is not enough to only look at the reverberation time. By taking other measurements in consideration, the acoustical evaluations get more complete and accurate The ISO 3382-1 describes some of the newer measures, such as relative sound pressure level, early or late response and lateral energy fractions. STI and clarity are also described in the standard. Parts of the standard introduce how to obtain these newer parameters, but they are not a requirement of the formal standard [23]. However, ISO 3382-1 is not suitable to use for measurements in ordinary rooms [22].

5.1.1 Design of the case study

Since one part of the purpose is to investigate the sound environment in hospitals, the sound pressure level is evaluated in the case study. This is done to identify what types of sources that exist, how loud they are and how loud the general activity is. The loudness of activities varies a lot within a hospital since there are different categories of departments. The conditions of patients, work and activities differ a lot between departments, further increasing the variations in loudness.

The reverberation time is evaluated since it is essential for the perception of the sound environment. There are also given values of the reverberation time, which should be fulfilled according to The Swedish National Board of Housing, Building and Planning. Their regulations contain provisions and general recommendations regarding protection against noise.

The literature review and the motivation indicate strongly that both speech intelligibility and clarity are of high importance in hospital spaces. These parameters are important to ensure patients comfort and well-being, but also from a safety point of view. The communication between patients, doctors, staff and visitors needs to be satisfying and good enough. Therefore were also speech transmission index, STI, and the speech clarity evaluated.

To summarise, the following parameters will be evaluated through the case study, either with measurements or modelling:

- Reverberation time
- Clarity
- SPL
- STI index

5.2 Swedish building regulations and standards

Swedish standards and building regulation are studied before the measurements, in order to make the intended measurements and the results as accurate as possible. The standards are needed to be able to make an evaluation and analysis of the result from the measurements.

5.2.1 Sound classification in BBR

BBR is the Swedish building regulations that are valid for new constructions, additions and changes of buildings. Swedish standards are a complement to BBR and are a support during planning, design, production and control of a building. Swedish standards have four different sound classifications, where class C is the minimum requirement to fulfil the building regulations [1]. See Table 2 for description of class A-D.

Table 2. Sound class A-D [1]

Class A	Class A corresponds to very good acoustical conditions.
Class B	Class B corresponds to better sound conditions than sound class C. Affected individuals may still sometimes be disturbed. This class is the minimal requirement if a good living environment is demanded.
Class C	Class C corresponds to sound conditions that are applied as minimum requirements in Swedish buildings.
Class D	Class D corresponds to the sound conditions that are applied when class C cannot be achieved, for example when renovating a building.

5.2.2 Sound classification of spaces in buildings

Swedish Standard 25268:2007 is valid for different types of premises, such as institutional premises, rooms for education, preschools and leisure-time centres, rooms for office work and hotels. Chapter 5.6 is about sound classification of healthcare premises, where the demands for the different sound classes can be found.

The values refer to the arithmetic mean values of the octave bands 250 - 4 kHz, where the deviation in an individual octave shall not exceed the value with more than 0,1 seconds. In spaces where people spend more than temporary time, the value may not exceed 0,2 seconds over the required value at 125 Hz. In sound class D or in rooms where people stay temporarily, such as washrooms, corridors or stairwells, there are no requirements for reverberation time in at 125 Hz. In rooms where the vocal communication is central, it is accepted with 0.1 seconds longer reverberation time for sound class A and B in the octave band 125 Hz [24].

In the spaces where speech conditions are a priority, the reverberation time should neither be shorter nor longer than the tabulated value. For spaces where low sound levels are a high priority, it is helpful to reduce the reverberation time further to get the sound environment that is desired [24]. See Table 3 for values of maximum reverberation time.

Table 3. Maximum reverberation time T_{20} in different types of rooms in healthcare premises [24].

	T20 (s)			
	Sound class			
Type of room	A	B	C	D
Spaces with specific needs of a damped sound environment, for example, rooms for intensive care, recovery and speech therapy.	0,4	0,5	0,5	0,6
Rooms that people are visiting for longer times. For example rooms for patients, examination, treatment, childbirth and physical therapy. Also operation halls, laboratories, day rooms and waiting rooms.	0,5	0,6	0,6	-
Rooms where people stay temporarily, such as elevator halls, rest rooms and entrances.	0,6	0,8	0,8	-

Further on, the SS 25268:2007 contains maximum values of sound levels from installations for each sound class, see Table 4. The standard also includes maximum values of dimensioned sound levels from traffic and other similar type of sources, see Table 5.

Table 4. Highest A and C-weighted SPL from installations in different types of rooms in healthcare premises [24].

	L_{pA} (dB) **Sound class**				L_{pC} (dB) **Sound class**			
Type of room	A	B	C	D	A	B	C	D
Space for patients' sleep and rest, or space requiring silence. For example patient rooms, hospital rooms and recovery rooms.	26	30	30	30	46	50	50	-
Spaces for active care work, individual work and different types of staff rooms. For example expeditions, offices, treatment rooms, operation rooms, rooms for physiotherapy, laboratories and rest rooms.	30	35	35	40	50	55	55	-
Other spaces where people stay more than temporary. For example, day rooms, waiting rooms and dining rooms.	30	35	35	40	55	-	-	-

Table 5. Dimensioned sound levels from traffic and other sources in different types of rooms in healthcare premises [24].

	$L_{pA,eq}$ (dB) Sound class				$L_{pAF,max}$ (dB) Sound class			
Type of room	A	B	C	D	A	B	C	D
Space for patients' sleep and rest, or space requiring silence. For example patient rooms, hospital rooms and recovery rooms.	26	30	30	35	41	45	45	50
Spaces for active care work, individual work and different types of staff rooms. For example expeditions, offices, treatment rooms, operation rooms, rooms for physiotherapy, laboratories and rest rooms.	30	35	35	40	45	50	50	60
Other spaces where people stay more than temporary. For example, day rooms, waiting rooms and dining rooms.	35	35	40	45	-	-	-	-
Rooms where people stay temporarily, such as elevator halls, rest rooms, cloakrooms and entrances.	40	45	-	-	-	-	-	-

6 Measurements

Measurements of reverberation time and sound sources in the room are done. An ocular inspection is performed and potential noise sources in the room are identified and recorded. The clarity and the STI are investigated later on in chapter 8.

The results are evaluated according to the earlier described Swedish Standard. The measurements are done in a patients room at an orthopedically clinic on Skåne University Hospital, in Lund.

6.1 Description of the case

A description of the room is done in this section. Possible sound sources in the room are listed, the geometrical structure of the room and the surfaces are described. The results from the ocular inspection are described in Table 6. A detailed drawing of the clinic can be found in Appendix I, where the room is marked out with green lines.

The clinic gives treatment to patients with urgent orthopaedic diagnoses or patients who are admitted for planned orthopaedic surgery. The most common diagnoses on this orthopedically clinic are hip fractures and osteoarthritis. The clinic has free visiting hours during daytime and room for 28 patients in total [25]. There are different types of rooms in the clinic, both rooms that are built for one or several patients.

The room where the measurements are done is built for four patients. In this room, patients are only hospitalized for one day or for shorter periods. The room is also used for patients who are to awake and recover after their surgery. The patients are mostly in an all right condition and are able to manage on their own.

The room is rectangular, with one side covered with windows. See Figure 11 and 12 for illustration of the ceiling.

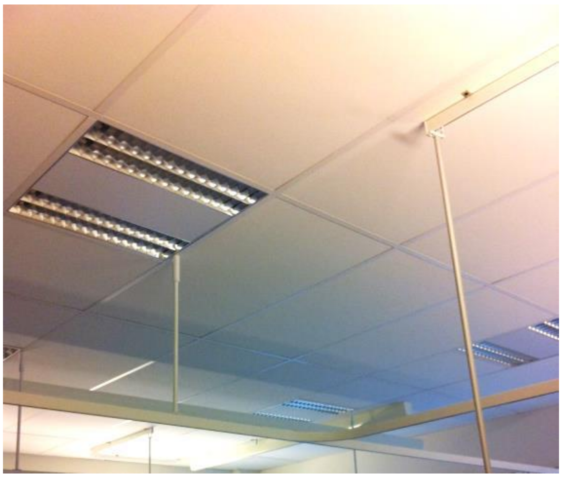

Figure 12. The ceiling of the room.

Figure 11. Close up of one of the tiles that covered the ceiling of the room.

Table 6. Result from ocular inspection and information about room 6.

Location	Skåne University Hospital, located in Lund. Room number 6 at the orthopedically department 12.
Walls and slabs	Load carrying walls in concrete, concrete slabs, gypsum interior walls
Surface materials	Gypsum, plastic flooring, painted concrete, ceiling tiles
Dimensions	See Figure 13
Volume	94.6 m^3
Height	- The height up to the ceiling is 2.45 m in the entrance of the room and 2.83 m in the rest of the room. - Height from ceiling up to the roof is 1.2 m in the entrance and 0.8 m in the rest of the room.
Furniture	Four beds, two wooden chairs, separating fabric curtains between beds and four tables.
Sound sources	Alarms, pressure equalizing mattresses, staff talking, moaning and talking patients, people walking or running in the hallway and noise from an ongoing renovation of the hospital.
Ceiling	Ceiling tiles made of mineral wool, thickness of 20 mm.
Other	Six windows along the long side of the room, two doors, supply diffusers under each window.

The following Figure 13 shows the dimensions of the room in which the measurement is performed.

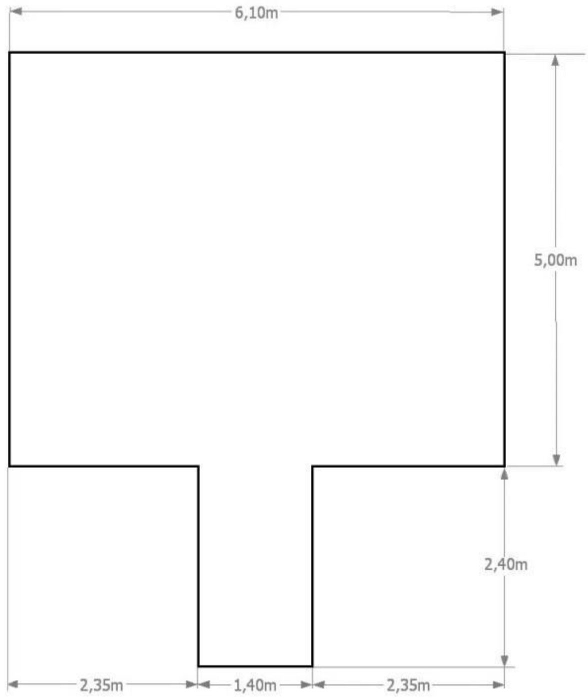

Figure 13. Dimensions of the room.

6.2 Measurements of reverberation time

The measurements are done according to the standard SS-EN ISO 3382-2:2008 ‘Measurement of room acoustic parameters’. The interrupted noise method was used, which mean that the decay curves of the sound are obtained by a direct recording of the decay of sound pressure level after exciting a room with broadband or band-limited noise

An omnidirectional loudspeaker is put in two different source positions, where one is in a corner of the room, see Figure 14. The loudspeaker generates broadband noise at a level of 90 dBA, this to ensure that the generated noise is at least 45 dB higher than the background noise for each frequency band. For every source positions, there are three different microphone positions equally spread across the room, which gives six microphone positions in total. See Figure 15 for an overview of the room with positions.

To reduce the risk of influence from standing waves, the microphone positions are placed at least one meter above the floor. The positions were also placed at least one meter from other possible reflecting surfaces. Two decays are registered for every microphone position. The measurement equipment, a 2270 Brüel & Kjær sound level meter, is calibrated before and after the performance of the measurements [26].

Figure 14. Omnidirectional loudspeaker.

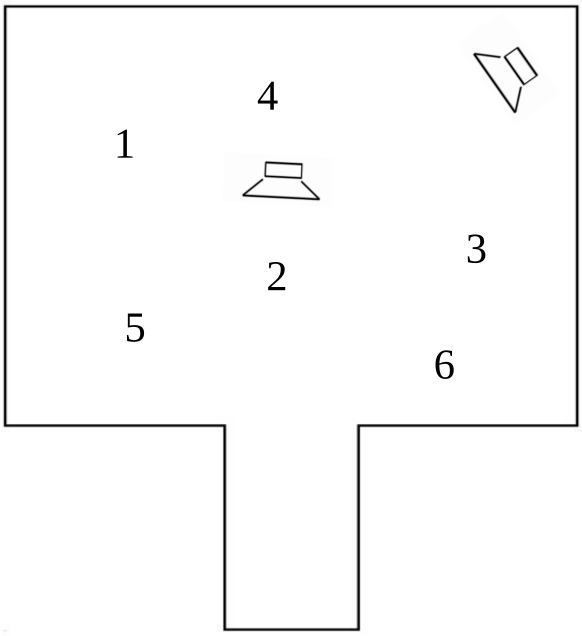

Figure 15. Positions of microphone and loudspeaker.

6.2.1 Results

Figure 16 shows the results from measurement of reverberation time, T30, for the room. Table 7 shows the results for octave band 250-4000 Hz.

Table 7. Reverberation time T30 (s), which is to be compared with guidelines values from BBR, presented in previous chapter.

T_{30} (s)			**Frequency (Hz)**		
125	250	500	1000	2000	4000
0,39	0,34	0,35	0,37	0,41	0,42
Mean value = 0,38					

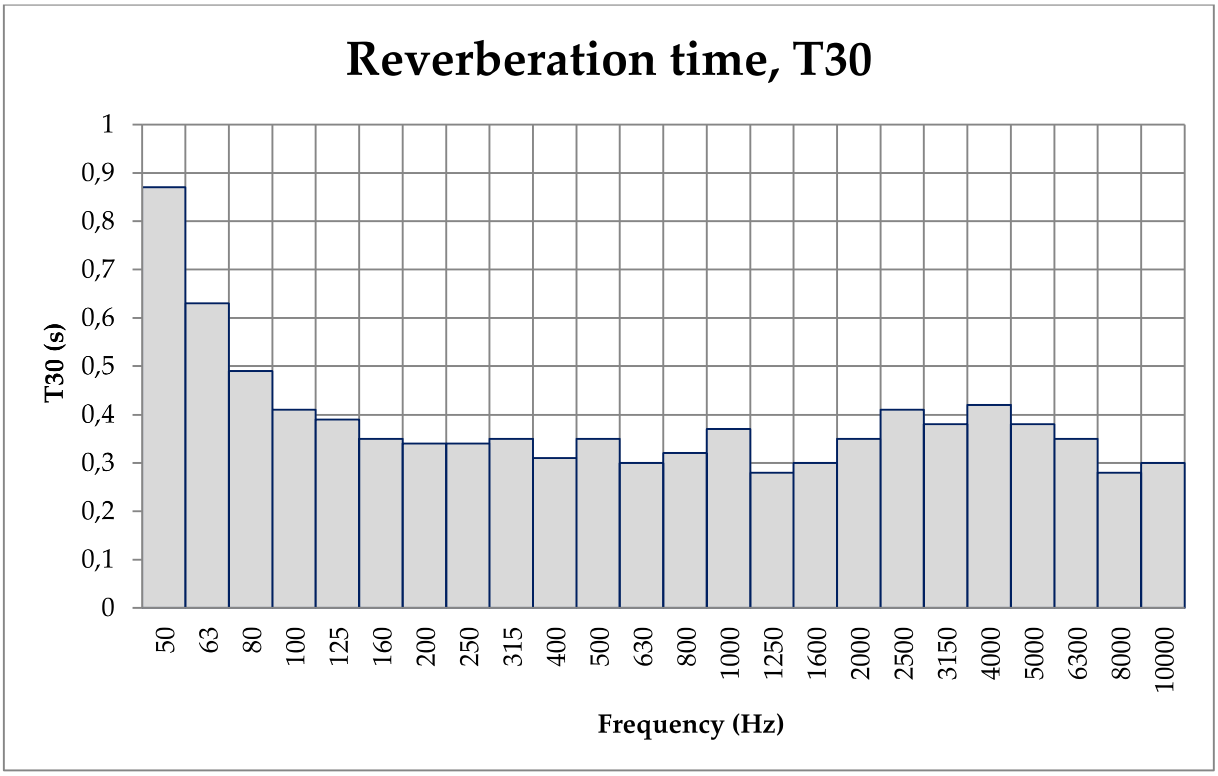

Figure 16. Reverberation time T_{30} (s) over frequency.

6.3 Measurement of sound pressure level

The measurements are done according to SS 025263 ‘Measurements of sound pressure level in rooms’. The attempt consists of measuring sound with short duration in the direct field. The sound pressure level is measured with a sound analyser in a number of positions. The microphone positions were placed 1.0 m from reflecting surfaces.

Microphone positions

10 different measuring positions are used. Position 7 and 9 are located in the hallway outside of the room and are therefore not visible in the picture. See Table 8 and Figure 17.

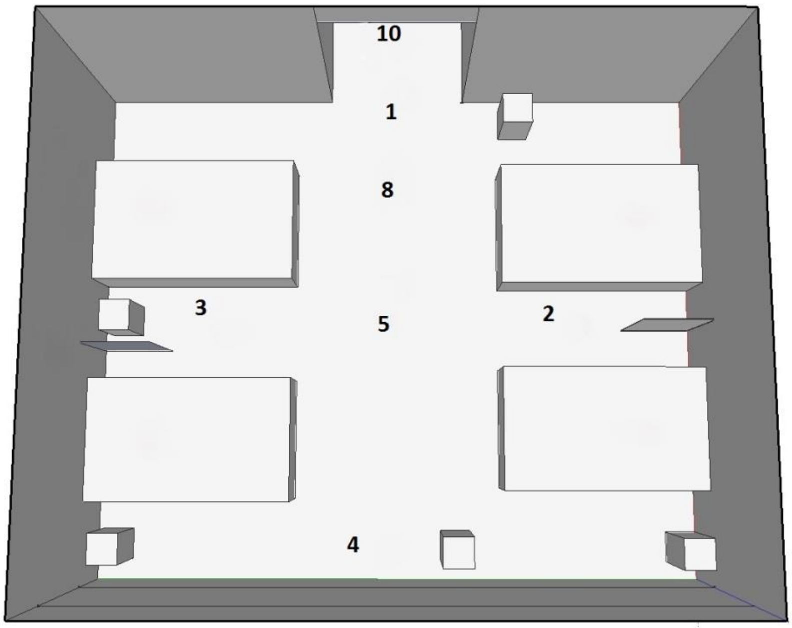

Figure 17. Illustration of measuring positions.

Table 8. Description of the different measuring positions.

Position	Description
1.	In the entrance of the room
2.	Next to patients bed
3.	Next to patients bed
4.	Next to supply diffusers
5.	In the middle of the room
6.	Sounds from ongoing renovation of the hospital
7.	Alarm in the hallway outside the room
8.	Near the entrance of the room
9.	In the hallway outside the room
10.	In the entrance of the room, next to the door

6.3.1 Results

Table 9 shows results from measurements of sound pressure levels in the room at the different positions. Figure 18 shows the sound pressure levels in the different positions in octave bands. Figure 19 show the SPL for position 7 and 9 in the hallway, together with position 10 that is near the entrance of the room. The average SPL in room 6 is shown in Figure 20. See appendix III for more detailed values of the results.

As can be seen in Figure 18, there are a lot of difference between the measuring positions. This may be explained with the different types of character of the sound in the positions, for example will the sound of an alarm be louder than the SPL measured next to the patient's bed. To make interpretation and analysis easier, an average of the positions inside the room is marked out in Figure 19. Figure 19 shows a connection between the SPL in the corridor and the SPL near the entrance of the room (position 10), which is expected.

Table 9. Measured L_{Aeq} and L_{Afmax}.

Position	L_{Aeq}(dBA)	L_{AFmax}(dBA)
1.	45	54
2.	35	44
3.	39	58
4.	34	44
5.	53	59
6.	54	57
7.	52	63
8.	41	47
9.	52	67
10.	41	50

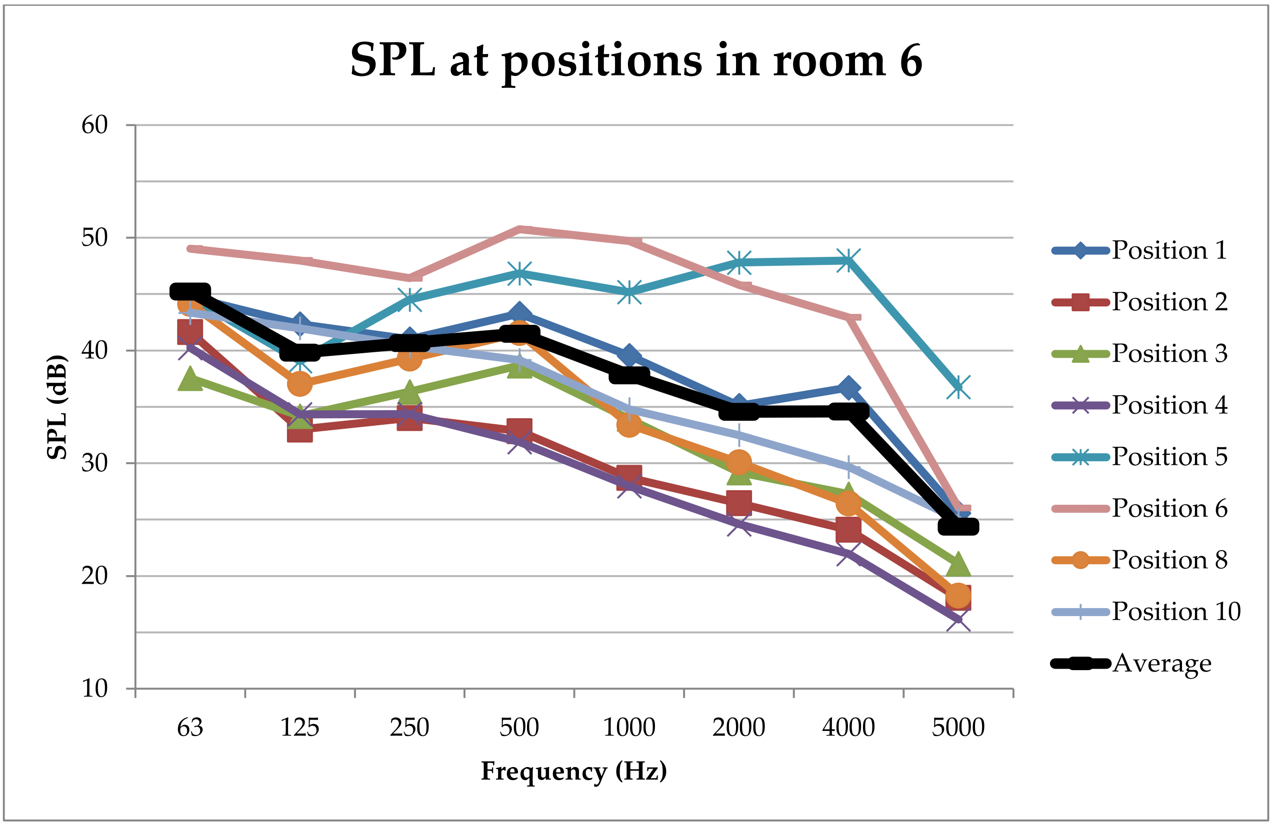

Figure 18. SPL at the different positions inside the room. Positions 7 and 9 were situated outside of the room and are therefore not a part of the figure. An average of the positions is marked out with a thick black line. See Table 8 for description of positions.

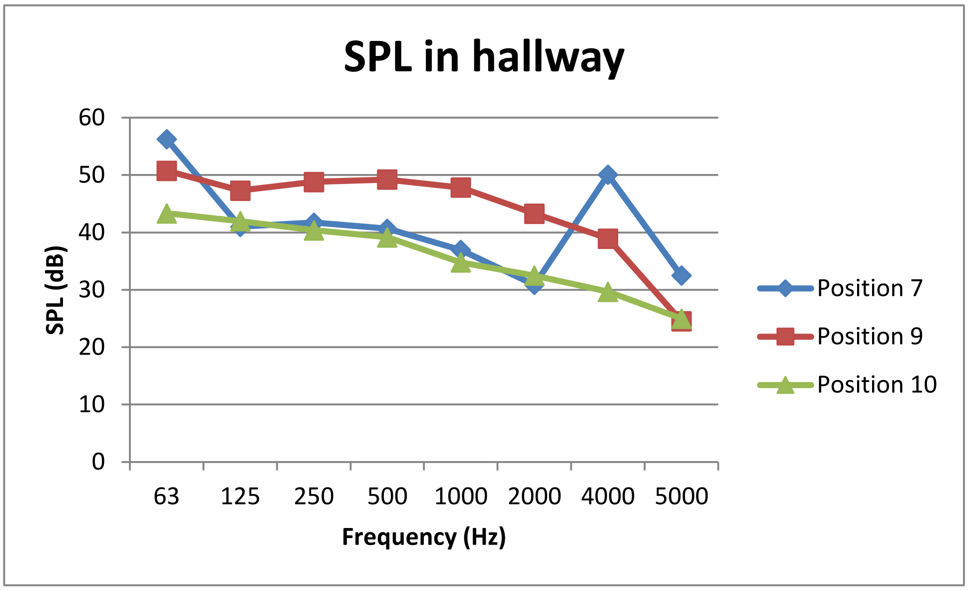

Figure 19. SPL for position 7 and 9 in the hallway, together with position 10 that is near the entrance of the room.

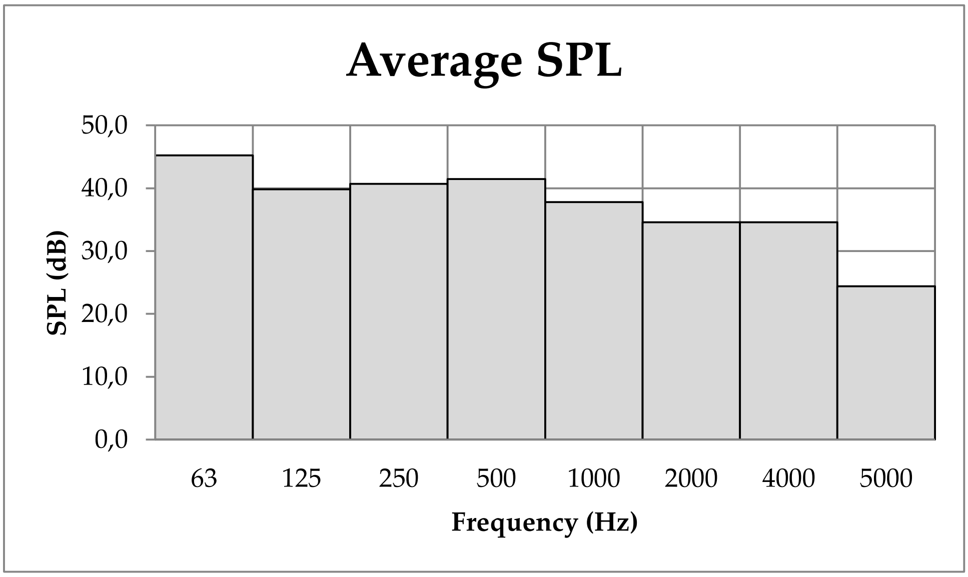

Figure 20. Average SPL based on the measuring positions in the room.

7 Interviews

Interviews are conducted with four persons from the medical personnel at the orthopedically clinic, department 12 in Skåne University Hospital. The people that participate in the interviews often visit the room during their working hours and are well familiar with it. The participants are both men and women, have varied age and have worked in the department for different periods of time. See appendix II for the complete interview formula.

7.1 Sound environment in room 6

Most of the participants have the opinion that the sound environment in the room is appropriate for its purpose. The participants think that the sound level in the room mostly feels normal and not too loud, if the patients are calm and still. They claim that the situation can be totally different in other similar rooms with four patients, where the patients that are in much worse conditions are taken care of. The patients in room 6 often keep a lower profile, since they mostly are in a better condition and state. The majority of the patients are usually day surgery patients. They are more mobile and independent than the average orthopaedic patient.

The most common sound sources according to the participants are patients or staff talking, the pressure equalizing mattresses that are used for the beds, alarms, radio playing, squeaking bedframes and bedside Tables. The one source that all participants mention is noise from the hallway outside the room. The door between room 6 and the hallway is always opened. The participants experience that the levels of sound were highest during the activities in the morning. The sound level usually decreases during the day, after 10 AM.

The participants find it difficult to come up with sound sources that could be experienced as positive. Sound sources that are experienced as negative are noise from the hallway, patients and personnel talking. If the windows are open traffic noise can be heard, and that is also experienced as a negative noise source.

7.2 Effects on patients

The participants think that if a patient is making noise because of pain or other emotions, this noise can affect other patients negative. Other patient can get nervous or worried because of noise like this. One participant said that the patients are affected in a negative way when hearing other people talk in the room. This can occur when doctors or other personnel are on their rounds and when there are visitors in the room.

One participant said that the curtains which are placed between the beds just works for the visual privacy of the patients. They do not shut out unwanted sound, since they are too thin. Some of the participants are of the opinion that since the sound levels in the room are experienced as low, it is not a problem for the patients in this case.

7.3 Work environment

The participants all agreed on that the work environment is satisfying and that it is not so very noisy in room 6. One participant means that if a patient is in pain and starts screaming, the work environment becomes tense and stressful. Another participant mentions the noisy alarms which are located across the entire department. The alarm sound can sometimes be stressful and annoying, but it was not a thing that the participant usually reflected over. A common work situation in the room is illustrated in figure 21.

Figure 21. Work situation in a room with four patients [25].

7.4 Summary

The general impression is that the participants are satisfied with the sound environment in the room. There are a number of sound sources that are experienced as annoying and that could affect the patients in a negative way. The most substantial and annoying sound sources come from the hallway outside room 6. The participants points out that the sound level is experienced as much worse in other four-bed room. This since the patients in room 6 often is in a better medical condition. Overall, the participants give a quite stressed impression and some of the personnel are reluctant to the interviews. This reluctance probably depends on the personnel's busy schedule.

8 Modelling and simulations

A room with the same geometrical properties as the one in the case study is designed in the 3D modelling program SketchUp. The model is imported into the acoustical software Odeon where analyses and evaluations can be done. Before analysing the model, material for all the surfaces in the room are selected from a database in Odeon. Sound sources are placed in the model to simulate the real case.

8.1 Odeon software

Odeon is a software for acousticians that can simulate the interior acoustics of a building. Odeon is based on an image-source method combined with ray tracing. The acoustics can be predicted and listened to with the geometry of a room and its surface materials as input data [27].

The program is used by first modelling a room in 3D and then specify material parameters for each surface in the room. It is possible to place out the desired type of sound source in the model. After simulations in Odeon evaluations and analyse of for example different absorbing materials and the reverberation time can be done. The 3D modelling program SketchUp is often used as a plugin for easy handling of the modelling [27].

8.2 Simulations

The room is first modelled in SketchUp, which is used as a plug in with Odeon. Five receivers are placed in the room, four on each bed and one in the middle of the room. Five point sources are placed in the room for the simulations, with the same values of SPL that was obtained during the measurements. See Figure 22 below for illustration.

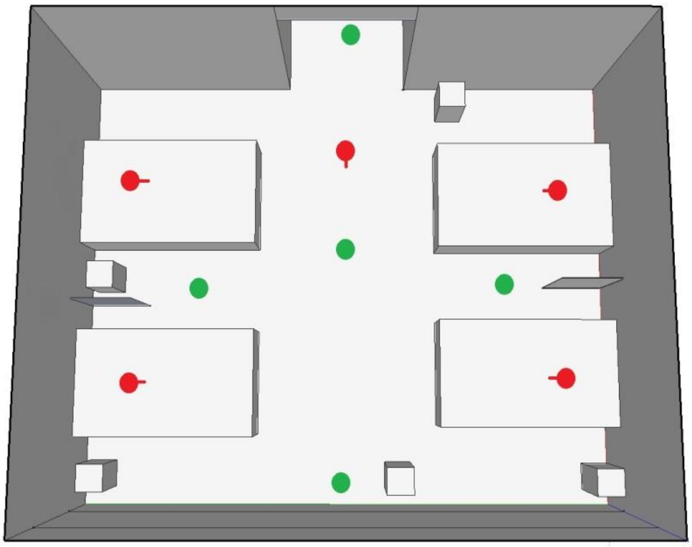

Figure 22. Illustration of the simulated case. Receivers with their directions are marked out in red and sound sources in green.

Materials are assigned to the surfaces of the room, they are chosen to resemble the case study as much as possible. Simulations are done until the reverberation time matches the results that are presented in the measurement chapter as close as possible. The adjustment is done by changing the amount and properties of the absorbing materials of the room. The simulations are done with focus on matching the octave bands 250-4000 Hz, since they are the octave bands that the standards requirements are valid for.

8.2.1 Results from simulations

Following section includes the results from the simulations, more detailed values and data for each receiver can be found in Appendix III. In Table 10 results of STI are presented. These values are considered as excellent according to the objective scale of STI. Results of clarity are presented in Table 11, this is the sound that is received within the first 80 ms. Results of reverberation time are presented in Table 12. The results meet the requirements for sound class A, see Table 3 in chapter 5.

As mentioned earlier, the simulations were adjusted so that the simulations would match the values from the measurements. A slightly difference is seen in the octave band 250, 1000, 2000 Hz, with a maximum difference of 0,01 s. See Table 12 and 7 for comparison.

Table 10. Results from simulations of speech transmission index (STI) in Odeon.

Speech transmission index (STI)		
Minimum	Average	Maximum
0,82	0,84	0,86

Table 11. Results from simulations of clarity (C_{80}) in Odeon.

C_{80} (dB)		Frequency (Hz)			
125	250	500	1000	2000	4000
18,8	16,8	15,3	14,8	13,9	16,6

Table 12. Results from simulations of reverberation time (T_{30}) in Odeon.

T_{30} (s)		Frequency (Hz)			
125	250	500	1000	2000	4000
0,33	0,33	0,35	0,38	0,40	0,42

8.3 Change of design

In this section an example of how the acoustical design of the room could be changed is presented. The changes are developed through simulations with different types of materials. After six simulations with different combinations, the example with best improved values is chosen. In this particular room, the acoustical conditions met the requirements for sound class A when it came to reverberation time. However, the SPL was too high and by redesigning the room the acoustical environment could be experienced as more quiet and calm.

There are obviously many possibilities of how to vary the design of the room. The new design is chosen from a practical and medical point of view. To achieve improvements for the sound environment in the room, wall absorbers are placed on the walls above each patient bed. Wall absorbers are also added to the wall section under the windows, where there was a wood panel before. Curtains between the beds are changed to a heavier and more absorbent fabric. The ceiling is replaced with a kind that is accustomed to hospital environments. See Figure 23 for an illustration of the suggested design.

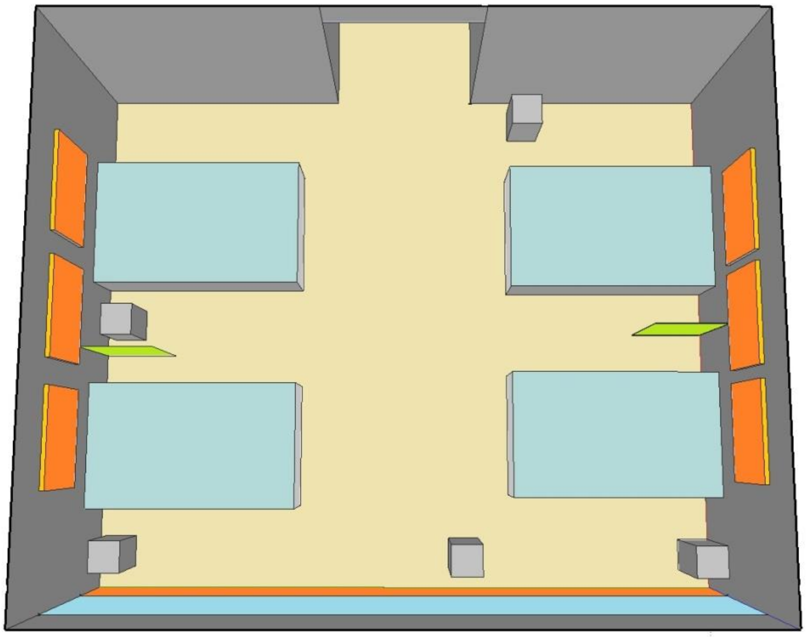

Figure 23. Suggestion for new acoustical design, seen from above. The orange parts are wall absorbers added on two parallel surfaces. A wall panel is also added underneath the window sect Results from simulations of new design in Odeon of Clarity (C_{80}).ion. Heavier and more absorbent fabric is added to the curtains between the patient beds.

8.3.1 Results of new design

Tables 13-15 show results of the new design suggestion. The average value of STI in the room has improved with 4 percentage points speech clarity increases with approximately 6-8 dB for frequencies 250-8000 Hz. The reverberation time has slightly decreased. The results from the simulations are further discussed and analysed in the next chapter.

Table 13. Results from simulations of speech transmission index (STI) with the new design.

Speech transmission index		(STI)
Minimum	Average	Maximum
0,87	0,88	0,89

Table 14. Results from simulations of Clarity (C_{80}) with the new design.

C_{80} (dB)			Frequency (Hz)		
125	250	500	1000	2000	4000
18,0	22,7	21,7	19,6	19,3	19,0

Table 15. Results from simulations of reverberation time (T_{30}) with the new design.

T_{30} (s)			Frequency (Hz)		
125	250	500	1000	2000	4000
0,3	0,29	0,32	0,35	0,39	0,4

8.4 Comparison of the designs

To get an overview of the differences between the original and new design, comparative diagrams are done. The following Figures 24-26 shows a comparison between the original and the new design alternative. The results are further discussed and analysed in the next chapter.

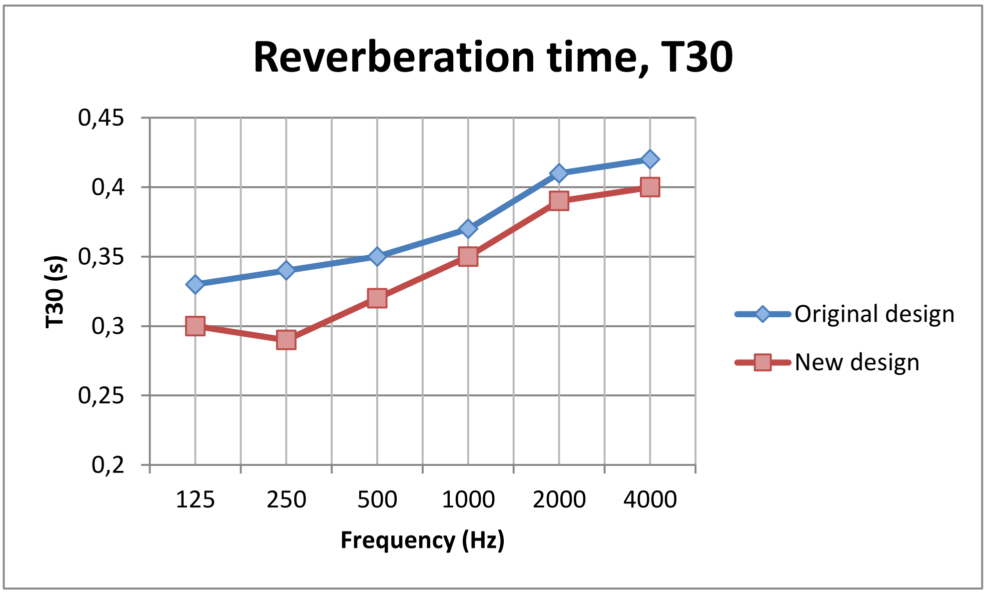

Figure 24. Comparison of reverberation time with the original and new design.

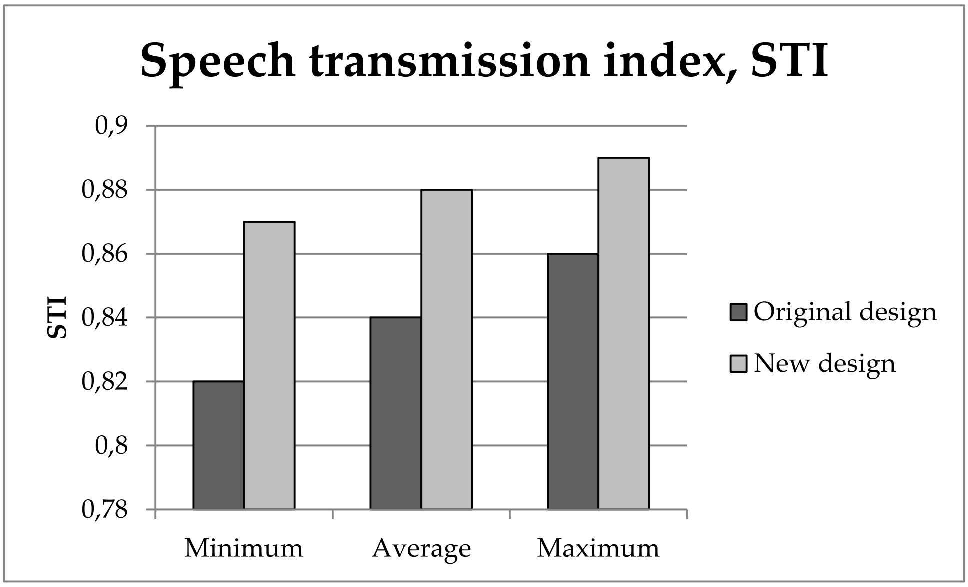

Figure 25. Comparison of STI with the original and new design, zoomed in on the upper part of the percent stacks.

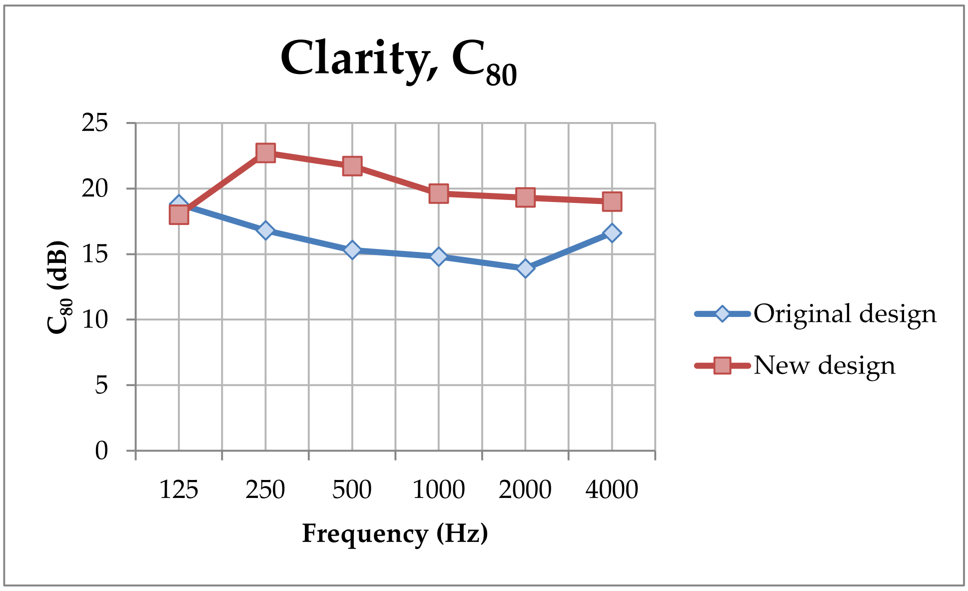

Figure 26. Comparison of clarity with the original and new design.

9 Discussion

This chapter consists of a discussion, where the literary review, results from measurements and modelling are discussed and analysed. Opinions and results from the interviews are also an important part of this discussion. The chapter will form the guidelines of how to design rooms for patients in hospitals, with the goal of achieving a satisfactory sound environment.

9.1 Sound environment in hospitals

Through the motivation of the thesis, conclusions can be drawn that a noisy environment has a lot of negative effects on humans. Exposure of noise may lead to negative cardiological consequences such as high blood pressure and increased heart rate. These consequences are often temporarily, though long time exposure of high sound levels has been proven to cause permanent high blood pressure.

A satisfactory sound environment has positive effects for both patients and personnel. To begin with, a couple of studies have investigated effects of noise upon health and healing of patients in hospitals. Many of these studies show that the consequences might be fatal. Stress, high blood pressure and sleeping disorders are common problems that are mentioned in earlier studies. Patients usually belong to the vulnerable group, since they often have medical problems or particular diseases. Elderly and weak persons are by natural reasons also over representative among patients. The sound environment is therefore an important aspect that should be highly prioritised.

A further aspect is the recovery of patients, which could be affected in a negative way by high levels of noise. Too high sound levels during daytime interrupt patients in their recovery and rest. At night time sound levels are usually bits lower, but still enough loud to interrupt patients in their sleep. A more quiet and pleasant sound environment could lead to shorter recovery time for patients. This will in addition result in positive effects, such as shorter treatment times, more circulation of patients and less waiting time for people who need to be hospitalised or treated for their disease. These eventual effects are things that the whole society would serve on. The positive effects would lead to both economic and social profit.

Unwanted and disturbing sound at workplaces may lead to increased stress. A noisy environment also leads to difficulties with concentration, distraction and annoyance. Too much persistent noise at workplaces makes it harder for people to perform their mentally challenging work. It is mainly high frequent noise and intermittent sound sources that disturbs the human concentration. Linked to sound environments in hospitals, common sources of this type are for example alarms, ventilation systems, pagers and intercoms. Work that is performed at hospitals is in addition often mentally challenging, with high demands on the level of concentration due to the safety of patients. The high levels of noise may lead to staff feeling stressed and anxious at work. Nowadays many hospitals suffer from lack of medical personnel, often because of financial cuts, which increase the workload. This in combination with a noisy work environment lead to unacceptable conditions for the hospital staff.

A few numbers of studies have been done on the effects that a noisy sound environment has on hospital staff. But the study “Acoustics and psychosocial environment in intensive coronary care”, describes that staff that work in a noisy and loud environment gets more tired and distracted, the speech intelligibility also gets worse. These consequences are a great hazard for patients and can lead to mistreatments and fatal misunderstandings. Mistakes may have effect on both patients and staff, it is clearly that a more silent environment is preferred in all cases.

Moreover, it is also of importance that visitors are able to communicate with patients and medical personnel. The quality of speech transferred to a listener needs to be high. As mentioned earlier in the thesis, it is harder to percept information and variations of the speech in a reverberant room with a lot of disturbing background noise.

9.2 Case study

The reverberation time is not exceeding any value of BBR's recommendations. This is probably due to the fact that there was a lot of absorbent material in the room, which reduces the reverberation time. There were a lot of fabric such as curtains, bedclothes and draperies between the patient beds. Furniture, thick bed mattresses and human presence in the room also have an impact on the results. According to the SS-EN ISO 3382-2:2008, up to two persons are allowed during measurements of reverberation time. However, these are the conditions that usually exist in the room and they are therefore authentic and realistic. As mentioned earlier through the thesis, it is not only the reverberation that affects how the sound environment in a room is experienced. Just because BBR's value is fulfilled does not automatically mean that the sound environment is satisfying for its purpose.

Discussion can be made about the conditions that existed when the measurements were performed. Activities and work at the clinic was ongoing and could not stop because of the measurements. Background sound and noise for the activities on the clinic could have had an impact on the results of the reverberation time. But since six measurements were made in total, the average of these measurements has credibility.

The interviews show that the personnel are satisfied with the sound environment in the investigated room. According to the interviews, room 6 is experienced as one of the most quiet and peaceful rooms in the clinic. But results from the measurements show that WHO recommendations for sound levels clearly are exceeded. The maximum value recommended by WHO for L_{eq} is 35 dBA. Values from the measurements clearly exceed this limit, with at the most 18 dBA. With these results in mind it is interesting to debate how the situation would appear in other rooms, where the sound level is experienced as much louder by all of the interviewed participants. The room that is studied is considered to be one of the calmest rooms according to the interviewed participants.

Patients in other rooms at the clinic are in a worse medical condition, they are therefore more vulnerable. These other patients could for that reason be more sensitive and affected in a negative way by high sound levels. They are more likely to be sensitive to disturbance of sleep and rest. Interesting and future work would be to look at other rooms, where these patients that are in a worse condition stay and where the sound levels are higher.

There are some sound sources that are experienced as disturbing by the participants. The most substantial and annoying sound sources come from the hallway outside room 6. When working in the same environment for a long time, it is easy to get used to the situation and the sound sources that exists in the background. This aspect was mentioned by some of the participants, who had difficulties with directly stating what type of sound sources that existed in the clinic. But since an evaluation of what sound sources that existed and an ocular inspection both were performed in the room, all of the sources are most likely identified.

Possible effects on patients and staff are not considered as a major problem among the participants.

The interviews were performed as open discussions. Underlying factors, such as dissatisfaction with other work-related issues could possibly have affected the interviewed personnel in their opinions. However, no major dissatisfaction was given in expression during the interviews by any of the participants.

9.3 Suggestion of design

A suggestion for improvements to the acoustical design of the investigated room is presented in the modelling chapter. This is a suggestion that was considered as possible and realistic to implement in reality. Other suggestions, with placement of the wall absorbers in a different way, could have given better results and values of the improvement. However, other alternatives would most likely mean more modifications and changes to the room or the building. This would lead to higher costs and more complicated solutions. The recommended design gives improvements in the reverberation time, clarity and STI index, which can be seen in Figures 24-26, under section 8.4, in previous chapter.

The new design will contribute with significantly better values of the clarity. This means that the number of early reflections has increased, which gives a positive effect on the intelligibility of speech. In other words, it would be easier to distinguish speech in the room compared with how it would be with the original design. According to values from the simulations, speech clarity increases with approximately 6-8 dB for frequencies 250-8000 Hz. An improvement can be seen in especially in the frequency of 500 Hz. Further on, there are no improvements in the lower frequencies 63-125 Hz.

Moreover, the design measures also have a positive effect on the STI index. The quality of speech that is transferred from speaker to listener becomes higher with the new design in comparison with the original. The average value of STI in the room has improved with 4 percentage points, which is a bit of an improvement. The minimum value and the maximum value of the STI have increased with 5 respectively 3 percentage points.

The reverberation time is slightly improved with the new design. A reduction of the reverberation time could decrease stress and improve wellbeing. In lower frequencies (63-250 Hz) reverberation time decreased by about 0.04 s in average. In the higher frequencies (500-8000 Hz) it decreased by 0.03 s in average. According to the measurements the reverberation time did not exceed any value from BBR in the first place. Since the value was satisfactory from the beginning and since the improvement is quite small, this improvement does possibly not affect how the sound environment is experienced in the room. However, less reverberations and echoes lead to a calmer and quieter sound environment. This is achieved since more sound is absorbed faster, sound waves will not be reflected as much as before which makes the sound level decrease.

Improvements of the acoustical environment may evidently be achieved with small measures. As mentioned earlier, this is only a suggestion of a possible design that is easy to accomplish. Other interesting alternatives could be measures directed at the sound sources of the room. For example shielding of medical equipment or more quiet alarms could shut out and reduce unwanted sound. In the case study, a curtain with heavy absorbent fabric to cover the entrance of the room would be an interesting alternative, since the most disturbing sounds came from the hallway outside. A different alternative would also be to install more absorbers outside in the hallway, which probably would be the most efficient solution to reduce that sound source.

10 Suggestion of design method

In this chapter a method containing acoustical guidelines are presented. The guidelines are supposed to be a support for achieving a satisfactory sound environment when building or designing rooms in hospitals.

Hospitals are a complex type of buildings when it comes to the acoustical aspects. The acoustical environment is only one of many parameters that affect patients' wellbeing and recovery. The usage of a room is very central and important, as the need for acoustical measures looks different for various types of activities.

The room that is studied in this thesis is adjusted for four patients. The previous discussion chapter mainly has focus on this particular type of room. As mentioned earlier in the thesis, it is important to have in mind that a lot of different room types exist in hospitals. The design method must be adjusted to for example rooms that are built for just one patient, operation halls, waiting rooms or emergency rooms.

The sound levels will vary due to what type of room that is going to be designed. An investigation of how high the sound levels are in an existing room, or how high sound levels could be expected in a planned room, should therefore be made. According to the literature review and the case study, several things contribute to the different characters of room types. Even within the same type of clinic or department of the hospital, rooms will vary a lot. The type of patients will vary, along with their medical types of condition. Numbers of patients and occupancy of the room also differ. The types of medical equipment that are needed and used are also different depending of the room type. The work of the personnel also varies between clinics and hospitals, some tasks are more demanding when it comes to concentration than others.

All these factors mentioned contribute to the sound environment of the room and it is therefore recommended that known facts about the room are stated and decided. Some room types need higher demands on the sound environment than others. It is of importance to design from both patients' and personnel's point of view.

As stated by the motivation, sound sources in hospital often are within the frequency range of 630 Hz and 2000 Hz, which is partly supported by the case study with values mainly within the range of 500-5000 Hz. Selecting sound absorbers that are most efficient in these frequencies is an important measure. In the suggested new design, wall panels are added to suitable areas of the walls, for example at parallel surfaces. Placement of absorbers at parallel surfaces prevents modes and flutter echoes. Placing absorption panels in corners minimises reflections that could strengthen sound levels in the room. When choosing absorbers, it is of importance that the material meets hygiene requirements. Surfaces need to be capable of being cleaned frequently. Reflective surfaces should be avoided to reduce the risk of reflections that may increase the reverberation in the room.

The demands in BBR should be fulfilled, but this is as stated before, not a guarantee that the sound environment will be satisfying enough for its purpose when it comes to spaces in hospitals. To further achieve a good sound environment other room acoustical parameters could be investigated. Supplementary requirements can be specified depending on what type of room, clinic or hospital that is going to be designed or rebuilt. It is essential to be able to understand spoken messages in hospital environments. Clarity and STI are two parameters that have been evaluated through the case study of this thesis. Declaring demands of these two parameters contributes to a sound environment where the speech is clear and the speech intelligibility is satisfying and good. This will improve the wellbeing of patients, visitors and staff. Requirements of clarity and STI will improve and increase the safety of patients and reduce the risk of misunderstandings and accidents.

It is of importance that the building overall fulfils high quality when it comes to performance and standard. Slabs and walls should be controlled so that the sound environment not is affected by transmitted sound or impact noise. Windows and doors should be of high quality and the surface of the floor should not be a material that reflects too much. Ceiling should be easy to clean and chosen with high absorption in the frequency range of 500-5000 Hz.

To reach a satisfying sound environment it is important to have acousticians and medical personnel as a help during the whole building process. It is very essential in the beginning of a project, during the planning and design phase. Having an acoustician as a support through the process is an insurance that the sound environment will be enough prioritised. Workshops and discussion about how to achieve a suitable sound environment could for instance be a suggestion.

10.1 Summary

Listed in Table 16 are a number of key steps that could be followed as a guidance when planning, building or rebuilding rooms and spaces in hospitals.

Table 16. Suggestions of key steps that could be followed as a guidance.

Actions	Description
Acoustical design team	Create an acoustical design team, including acousticians, architects, designers and experienced hospital personnel. Workshops and discussions are suggestions for actions in the planning process. Have the acoustical team available as a support and an active counsellor through the whole building process.
List of requirements	List requirements for the specific project. This can be values of for example clarity and STI, or that the reverberation time must be under a certain time but may also be other parameters that are stated in the ISO 3382-1:2009.
Usage of the room	Establish the usage of the room is central. Room types that are exist in hospitals are ward rooms, intensive care units, consulting rooms, corridors, receptions, and operating theatres.
Patients	Estimate what type of patients that will use the room, for example if it is a room for children or for patients that are extra sensitive or weak.
Identify sound sources	Identify which types of primary sound sources that will be found in the room and contribute to its sound landscape. Estimate within what frequency range the sound sources are or will be in.
Absorbent material	Add suitable absorbent material. Chose absorbers that are accustomed to an environment with high clinical demands. Acoustical ceiling, screens, curtains or wall panels could for example be used.

Placement of absorbers	Wall panels could preferably be used. Preferably place the panels on parallel walls or in corners.
BBR requirements	Have as a goal to fulfil BBR's demands of sound class A, but also have in mind that this step alone does not ensure a satisfying sound environment.

11 Conclusions

The conclusions of the thesis are presented in this chapter, along with suggestions of further work that could be done. The conclusions reflect and respond to the purpose that is presented in the introduction chapter.

11.1 Conclusion

Being exposed to noise may lead to negative cardiological consequences such as high blood pressure and increased heart rate. These consequences are often temporarily, though long time exposure of high sound levels has been proven to cause permanent high blood pressure. Stress and sleeping disturbance are also common effects for people that are exposed to a loud sound environment. Consequences like those mentioned lead to decreased wellbeing, through longer healing processes for patients and a stressed work environment for personnel. The patient safety is also at risk in an environment with high background noise, where it is hard to perceive spoken messages. According to a studied WHO report, sound levels have constantly been raising over the last five decades.

The acoustical design in hospitals is influenced by BBR’s sound classes together with requirement values of reverberation time and sound pressure levels from standards. Fulfilment of the requirements does not ensure that the sound environment is satisfying enough for its purpose. Other room acoustical parameters also have an influence in how the sound landscape in a room is perceived.

The case study of the thesis investigates SPL, reverberation time, clarity and STI. Measurements state that the SPL exceeds the recommendations from WHO with at the most 18 dBA, the sound levels are generally high in the room.

According to interviews the investigated room is experienced as the calmest and quietest on the clinic. The most annoying and negative sound sources are noise from the corridors and patients talking or complaining.

The clarity and STI are evaluated through modelling. By making a suggestion of a new design clarity is improved by 6-8 dB at frequencies 250-8000 Hz and STI increases with 4 percentage points. There is also a slightly decrease of the reverberation time. The new design suggestion consists of wall panels that are added to parallel walls and to one single wall. Patients’ beds are also screened by curtains.

Through discussion of case study and literature review suggestion of a design method is developed. Key steps in this method suggest that it is important to establish and decide the usage of the room. In this way an estimation of sound sources and the conditions of patients can be done. Declaration of certain acoustical requirements, for example clarity and STI, are recommended. Furthermore, creating an acoustical design team with architects, acousticians and personnel from the concerned hospital or clinic, is recommended.

11.2 Future work

The most important part of future work consists of making more measurements in other types of patient rooms on the clinic. This other types of rooms should preferably be different in terms of conditions of patients, levels of occupancy, type of sound sources and strength of sound sources. With investigation of SPL and interviews with concerned staff it would be possible to find suitable rooms.

Future work could also consist of making auralisations of how the sound environment could be experienced with the new design. This is possible to do in Odeon. In this way the new design of the room could be evaluated and compared with the original. This can be done by letting a number of listeners rate the sound environment objective before and after the changes of the design.

Implementations and testing of the developed guidelines is a possible work to continue with. This could be performed at a totally different department in the hospital, with activities and patient that differ from the ones at the orthopaedics.

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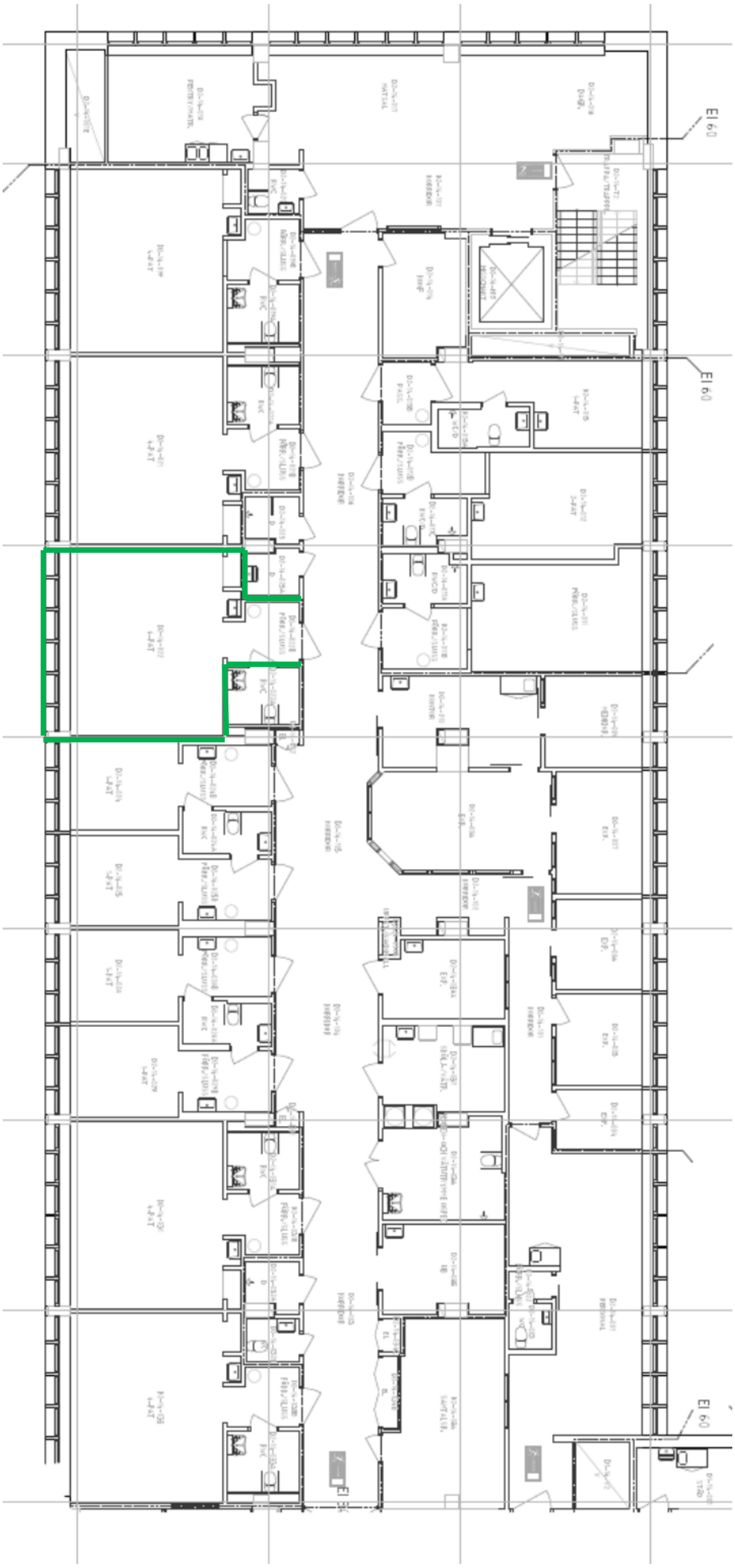
Appendix I. Layout of the clinic

The orthopaedic department 12, with room 6 marked out in green.



Appendix II. Interview questions

Interview questions for the personnel.

1. *How would you describe the sound environment in room 6?*

2. a) *Which are the most common sound sources in the room that you experience? (For i.e. ventilators, alarms, machines, people talking, staff talking)*

   b) *Which types of sound would you describe as positive respectively negative?*

3. *How do you experience that the sound environment affects the patients?*

4. *How do you experience that the sound environment affects the medical staff?*

Appendix III. Results from measurements

The following table present results of measurement of L_{feq} in octave bands 63-5000 Hz.

Results of L_{feq} from measurements.

L_{feq} (dB) **Position**	**Frequency (Hz)**							
	63	**125**	**250**	**500**	**1000**	**2000**	**4000**	**5000**
1.	45	42	41	43	40	35	37	26
2.	42	33	34	33	29	26	24	18
3.	38	34	36	39	34	29	27	21
4.	40	34	34	32	28	25	22	16
5.	45	39	45	47	45	48	48	37
6.	49	48	46	51	50	46	43	26
7.	56	41	42	41	37	31	50	32
8.	44	37	39	42	33	30	26	18
9.	51	47	49	49	48	43	39	25
10.	43	42	40	39	35	32	30	25

Appendix IV. Results from modelling

Following tables show results from modelling of the case study and from the improved design.

Speech clarity, C_{80} from the case study of room 6 at orthopaedics department.

C_{80} (dB)	**Frequency (Hz)**							
Receiver	63	125	250	500	1000	2000	4000	8000
1.	20,5	19	17,2	15,9	15,6	15,2	14,6	17,2
2.	19,5	18,2	16,2	15	14,9	14,5	13,9	16,6
3.	16,9	16,3	14,4	12,9	12,2	11,9	11,7	14,1
4.	21,7	19,8	17,4	15,9	15,4	15,2	14,7	17,6
5.	22,6	20,5	18,6	16,7	16,1	15,6	14,8	17,4

Speech clarity, C_{80} with new design.

C_{80} (dB)	**Frequency (Hz)**							
Receiver	63	125	250	500	1000	2000	4000	8000
1.	20	19	23,2	22	20,1	19,5	19,4	22,1
2.	18,4	17,3	19,5	18	17,1	16,6	16,5	18,9
3.	18,6	18,1	22,8	22	19,4	19,2	18,8	21,1
4.	18,5	17,6	24,2	23,4	21,3	21,2	21	23,4
5.	19,2	17,9	23,7	23,1	19,9	19,8	19,1	21,4

Speech transmission index, STI from the case study of room 6 at orthopaedics department

Receiver	STI index
1	0,86
2	0,83
3	0,82
4	0,84
5	0,85

Speech transmission index, STI with new design.

Receiver	STI index
1.	0,89
2.	0,87
3.	0,88
4.	0,88
5.	0,88

Reverberation time, T_{30} from the case study of room 6 at orthopaedics department

T_{30} (s)	**Frequency (Hz)**							
Receiver	63	125	250	500	1000	2000	4000	8000
1.	0,29	0,3	0,3	0,31	0,32	0,38	0,41	0,35
2.	0,35	0,38	0,36	0,35	0,36	0,4	0,42	0,38
3.	0,32	0,32	0,34	0,38	0,38	0,42	0,45	0,38
4.	0,31	0,33	0,35	0,33	0,39	0,39	0,38	0,37
5.	0,31	0,34	0,37	0,38	0,37	0,41	0,42	0,37
Mean	0,32	0,33	0,34	0,35	0,36	0,4	0,42	0,37

Reverberation time, T_{30} with new design.

T_{30} (s)	**Frequency (Hz)**							
Receiver	63	125	250	500	1000	2000	4000	8000
1.	0,28	0,33	0,3	0,32	0,4	0,42	0,48	0,3
2.	0,33	0,3	0,36	0,46	0,42	0,39	0,41	0,35
3.	0,32	0,28	0,24	0,25	0,32	0,41	0,38	0,28
4.	0,26	0,29	0,25	0,26	0,28	0,36	0,39	0,28
5.	0,28	0,3	0,28	0,29	0,33	0,37	0,33	0,28
Mean	0,29	0,3	0,29	0,32	0,35	0,39	0,4	0,3