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ON THE IMPORTANCE OF ROOM ACOUSTIC TREATMENT OF HOSPITAL CORRIDORS – ACOUSTIC INTERVENTION IN HOSPITAL VALL D'HEBRON (BARCELONA)

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ABSTRACT

It has been consistently shown that hospital premises should not ignore acoustics in their design if they are intended to enable comfort for both staff and patients. One space of a particular nature within hospitals is the often-"acoustically neglected"-corridor. Increasingly, these spaces are not being considered as a simple pathway to get from point A to B, but as truly complex open spaces with specific areas dedicated to rest, work (e.g. nursery stations) or even treatment in cases of space shortage. In oblong and open spaces such as corridors, it is particularly interesting to study sound propagation and privacy since, due to the morphology of the space, reverberation time alone does not completely describe discomfort and possible sources of distraction. Moreover, it is also of crucial importance to ensure that sound pressure levels due to everyday sources of noise are as low as possible. In this project, a corridor at Hospital Vall d'Hebron (Barcelona, Spain) was acoustically renovated by installing a class A sound-absorbing ceiling. Acoustic measurements of several parameters were performed both before and after the renovation. This study evaluates the results, analysing in detail the acoustic quality of such a singular space by means of both measurements and simulations.

Keywords: *hospital, corridor, sound propagation, sound privacy, comfort.*

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1. INTRODUCTION

Is a corridor "simply" a path to go from A to B or are they starting to increasingly become more like open spaces for e.g. resting or performing specific tasks? Regardless of the case, corridors are often "acoustically forgotten" in the design phase of healthcare premises, despite of their importance in terms of sound propagation (due to their morphology) and thus potential discomfort and lack of privacy. In broad strokes, corridors could be classified into:

- Transit logistic corridor: all hospitals have "logistical" corridors, whose main function is to ensure that people and equipment get from one point in the hospital to another. Although there are conversations within the corridors, the acoustic design is relatively straightforward, with priority being given to reducing noise levels and noise propagation.
- Ward/hospitalisation floor's corridors: in the past, ward corridors were often used by healthcare staff to (i) move from one patient room to another, (ii) route patients (in their beds) before and after an operation to/from the operating theatre, or (iii) where patients' relatives sat and waited in silence. Occasionally, and due to the lack of space for patients in the rooms, it is not impossible to also see patients in their beds recovering in the corridors, where not only communication with the staff takes place, but also where the first examination and even some recovery treatment or exercises are performed. It is also common that the patient is not visually protected; and as far as the sound environment is concerned, this type of corridors can be very noisy, which can in turn trigger negative effects on patients' health.

- Outpatient departments' corridors: these corridors (unlike ward corridors, as they are not usually operating at night) are very busy during the day. However, they are very noisy places due to communication not only between patients and staff, but also between relatives and triage/reception staff, as well as noise from on-site treatments in the corridor itself. Although the patients present here do not usually suffer from serious pathologies, they may feel unwell at the time (and even receive lengthy treatment there), so it is important to control noise levels so as not to aggravate this situation.

All in all, in open and voluminous spaces such as corridors, it is particularly interesting to study sound propagation and privacy since, due to the morphology of the space, reverberation time (RT) alone does not say much about annoyance and possible sources of distraction. It is important to ensure that confidential conversations do not "travel" and can be understood by others along the corridor. Moreover, it is also of crucial importance to ensure that sound pressure levels due to everyday sources of noise (movement of nursing staff, rolling of trolleys, bells, doors...) are as low as possible.

In this project, one of the corridors on hospitalisation floor 8 at Vall d'Hebron Hospital in Barcelona was acoustically renovated by installing a class A sound-absorbing ceiling. Acoustic measurements were taken both before and after the renovation. Specifically, in order to further quantify the improvement, noise levels were monitored during normal activity, and objective acoustic parameters of sound propagation and reverberation time were also measured. This paper will evaluate the results, analysing in detail the acoustic quality of a singular space such as a hospital corridor and further improvements to the implemented solutions will also be suggested based on simulated results.

2. ACOUSTIC REGULATIONS IN CORRIDORS

Standards and guidelines for room acoustics in healthcare are lacking in general and very few countries have mandatory regulations in this field. Even in countries with guidelines for other public buildings (e.g. schools), healthcare standards – and particularly detailed standards including corridors – do not often exist (and/or are included within other typology of space). As example, below are listed acoustic regulations of some European countries that mention corridors in healthcare premises:

- Spain: the National Building Regulation CTE DB-HR states that "common areas" should have sufficient sound absorption such that the equivalent sound absorption area, A (500, 1000, 2000 Hz), is at least 0.2 m^2 for each cubic meter of the volume of the enclosure. A "common area" (which is where the concept of corridor would fit in) is defined as areas giving service to several "units of use" (i.e. a part of a building that is intended for a specific use, and whose users are linked to each other, either by belonging to the same family unit, company, corporation or by being part of a group or collective that performs the same activity).
- Sweden: the newly published standard SS 25268:2023 sets a requirement for corridors of $T_{20} \leq 0.6$ s (250-4000 Hz). Likewise, equivalent sound pressure level limits from installations are established for ward corridors under the section "certain requirements for absence of disturbance", namely $L_{Aeq} \leq 35$dB, $L_{Ceq} \leq 55$dB. Moreover, maximum A-weighted equivalent and maximum indoor sound level from traffic and other external sound sources are set to $L_{Aeq} \leq 35$dB, $L_{Ceq} \leq 50$dB. In the standard, ward corridors and general corridors are distinguished (that latter categorised within "no requirements for absence of annoyance but with a need for speech intelligibility" and $L_{Aeq} \leq 40$dB).
- Denmark: the demands for corridors often coincide with the same target values as for examination/treatment rooms in healthcare premises; i.e. $T_{20} \leq 0.6$ s (125-4000 Hz), as stated in their national regulation SBI216/BR18.
- UK: the requirement stated in the norm HTM 08:01 is set in terms of a minimum area of absorption equivalent to a Class C-absorber, covering an area at least equivalent to 80% of the floor area. If materials of a better absorption class (Class A) are installed instead, the required minimum surface area would hence be reduced.
- France: the regulation "*Arrêté du 25 avril 2003 pour les établissements de santé*" is related to "all" public corridors (not only in hospitals) and the demands are established as the equivalent of 1/3 of the floor surface as a quantity of absorbing material (500-1000-2000 Hz).
- Norway: the demands for corridors set in the national standard TEK17 (referring to the norm NS8175:2012) are to be found in the paragraph for "public areas", where an upper limit for the reverberation time is established depending on the room height, i.e. $T_{20} \leq 0.2 \cdot h$ s.

- Finland: the standard SFS 5907:23 classifies buildings into classes A1 and A2 (new buildings) and A3 (for existing buildings), with different upper target values for reverberation time: 0.6 s for class A1 and 0.8 s for class A2, whereas A3 is limited to 1.3 s. The values for corridors in different types of buildings vary slightly, having hospital corridors and retirement home corridors more stringent target values than other premises[1].
- Germany: the DIN 18041:2016-03 states recommendations for hospital corridors with a "quality of stay", highlighting the minimum ratio between the surface area of absorption/room volume. Two different ratios, depending on the height of the room (<2.5m or >2.5m) are given.
- Holland: NPR 3438 sets a lower limit of absorption area to be added to the corridor of 1.8·S, S being the floor area (125-4000 Hz).

3. STATE-OF-THE ART

In 1859, Florence Nightingale wrote: "unnecessary noise is the most cruel absence of care that can be inflicted on the sick or the well". And still, almost two centuries after, noise is still often not accounted for in the design of healthcare facilities. Hospitals are buildings that house more people every day (due to demographic changes) and in which increasingly more complex tasks are performed (using more sophisticated equipment), i.e. there are more noise sources. Over the last decades, the average noise level in hospitals (both day and night) has increased dramatically [1]; in 2005, daytime values exceeded 70 dB, while nighttime values reached 65 dB (an increase of 15 dB during the day and 18 dB at night compared to 1960). Despite of this increase, hospital design has not changed sufficiently to accommodate these changes and new challenges, and consequently noise exposure in hospitals can be a common cause of health problems for both patients and staff.

3.1 Noise effects on patients

Regardless of the pathology a patient suffers from, noise will influence their recovery. When being ill, a person is more sensitive than usual to anything that takes one out of the comfort zone; a simple slamming door, for instance, can have a negative effect on recovery. Exposure to high noise levels has been shown [2] to disrupt patients' sleep, increase stress, delay post-illness rehab, increase nervousness, restlessness, agitation, cause psychiatric symptoms, and increase respiratory and heart rates. It is well known that the quality of sleep is of paramount importance (in general for human health and critical for the patient's recovery). Mood, behaviour, respiratory muscle function, healing time and length of hospital stay are just some of the possible effects of disturbing or depriving the patient's sleep [3]. Good room acoustics (by introducing absorption and thus decreasing noise levels) can, in part, not only speed up recoveries, improve sleep quality and reduce re-hospitalisations, but also minimise the need for additional medication [4,5].

3.2 Noise effects on staff

Albeit healthcare workers are (theoretically) healthy, noise exposure also affects this group, and not only their health but also the performance of their work. Communication errors (induced, amid others, by poor acoustics and/or a high noise levels) can lead to fatal errors, since, in an operating theatre, for example, the transmission of the message between staff during a surgery must be clear and intelligible so that the decisions taken are the right ones. In fact, in [6] it was shown that 70% of critical medical errors in emergency departments (ED) are due to "communication errors". Interviews in [7] revealed that 60.5% of staff found noise in the ED to be "very" or "somewhat annoying", and this can lead to, amid other things, fatigue (physical and mental) due to strained voices and extra attention to communicate correctly [8]. Regarding acoustics in corridors a recent study [10] revealed that nurses (whose majority of work takes place in corridors) are highly affected by sound and noise when it comes to prospective memory. This type of memory is essential for performing tasks such as remembering to administer medication to a particular patient at specific intervals. Specifically, one conclusion of [10] was that 40% of the tasks not performed were due to prospective memory failures. Much of the work of nurses takes place in corridors, so for a hospital to be efficient and safe, activity-based (acoustic) design should be prioritised.

4. CORRIDOR AT HOSPITAL VALL D'HEBRON

4.1 Description of the space

The corridors that were renovated are shown in Figure 1. They are located on the 8th floor of the hospitalisation building of the Hospital Vall d'Hebron. More specifically, the corridor belongs to the coronary unit (after-surgery patients). The longest one (shown horizontally in Figure 1) is 54 m long, whereas the short one (depicted as vertical in Figure 1) is 24 m. long. Both are 2.1 m width approx.

[1] If a corridor is classified as a treatment space, also STI ≥0.6 applies (796/2017 Decree of the Ministry of the Environment).

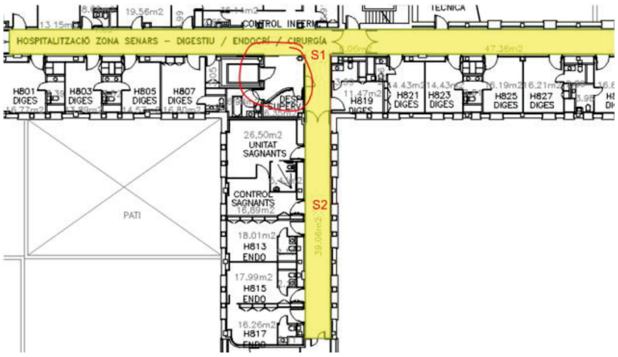

Figure 1. Corridors acoustically treated (in yellow). The long one (shown horizontal) is 54 m long, whereas the short, i.e. vertical one, is 24 m long. Both are 2.1 m wide approximately. S1 and S2 mark the sound monitor positions (cf. Section 5.3).

4.1.1 Prior to the acoustic intervention

The initial state of the corridor is shown in Figure 3. The floor was made of ceramic tiles, whereas the walls were plasterboard on top of masonry. Wooden doors were installed along the corridor as entrance to the bedrooms, and at the end of the corridor a glass sliding door was installed. The existing ceiling before the renovation was a perforated metal ceiling, with an acoustic lining on top. The maintenance department was not able to provide information about it to the authors about the exact model of the ceiling, but a qualified guess would be that the ceiling was either Class B or C absorption.

4.1.2 Post-acoustic intervention

A refurbishment was carried out in the corridors, and its final state is shown in Figure 3. The materials in walls and floor remain the same as before (just aesthetic change), however the ceiling is now different. The new system installed is an Ecophon Access (absorption class A – see Table 1 and Figure 2), allowing accessibility to the soffit.

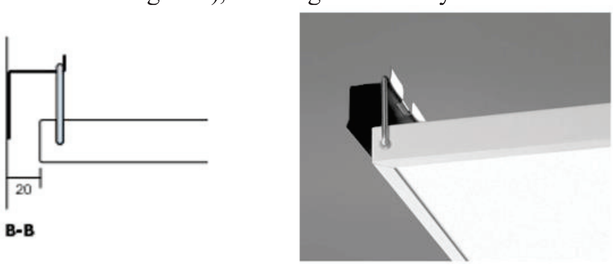

Figure 2. Acoustic ceiling (class A) installed. Ecophon Access. Good acoustics and accessibility.

Figure 3. Corridor before (upper picture) and after (bottom picture) renovation.

Table 1. Acoustic absorption of the Ecophon Access ceiling according to ISO 354 (and classified as per of ISO 11654). The thickness of the ceiling is 25 mm. Measurements results presented with ods of 200 mm.

f[Hz]	125	250	500	1k	2k	4k	α_w
α_p	0.5	0.85	0.95	0.90	0.90	0.80	0.90

4.2 Measurements

Acoustic measurements were performed aiming at assessing the acoustic quality of the corridor both before and after the intervention. More specifically, reverberation time and sound propagation measurements according to ISO 3382-2 and ISO 3382-3 respectively were carried out. Moreover, noise levels at two locations of the corridor were monitored, namely one at the intersection between both corridors (where the nursery station is located) and another one at the middle of the short corridor (cf. Figure 1). STI measurements as per of IEC 60268-16 were also done.

Figure 4. Measurement set-up for sound propagation measurements following ISO 3382-3 (upper picture) and placement of the noise monitoring device at two different locations (bottom picture).

5. MEASUREMENT RESULTS

5.1 Reverberation time (ISO 3382-2)

The measurements performed revealed (as depicted in Figure 5 and Table 2), that the reverberation time has not markedly changed after the intervention. The latter may be due to the fact that the old ceiling was already at least absorption class C, with acceptable absorption, especially from 1 KHz onwards. On top of that, visual inspection of the plenum showed much dust being accumulated in the cavity, hence potentially further increasing sound absorption at certain frequencies. Furthermore, a reorganisation of installations was done in the plenum after renovations, making it also difficult to compare directly both cases. However, an improvement in reverberation time is observed mainly at frequencies of 250 and 500 Hz in certain areas of the corridor. The 250 Hz octave-band is of paramount importance for attenuating mechanical noises such as rolling carts, HVAC systems, mechanical noises, etc. Likewise, 500 Hz is key for voice sounds. All in all, at certain positions, the average reduction of the reverberation time is within the JND stated in the ISO 3382-2 (5%), and thus most likely perceptible by the users (cf. Table 2).

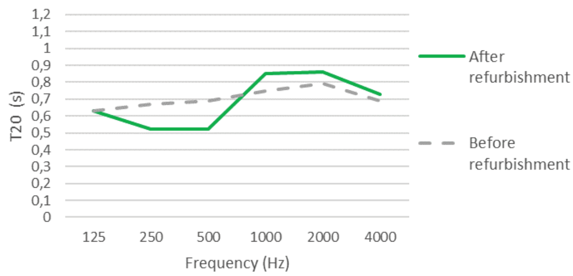

Figure 5. Comparison of the reverberation time measured before and after the refurbishment at 4 m from the noise source.

5.2 Sound propagation (ISO 3382-3)

The open plan office standard for sound propagation was employed to evaluate the sound propagation in the corridor. As illustrated in Table 2, there is a slight improvement in terms of $D_{2,S}$. Note that the materials in walls and floor remained the same after the renovation, being still fairly reflective. Although the change of ceiling brings a marked improvement in absorption, in narrow areas such as a corridor, lateral reflections from walls may appear, perhaps even more noticeable a highly absorbent ceiling, thus benefiting sound propagation. This side reflection effect, which can create flutter echoes, could be mitigated by absorption in walls and will be investigated in Section 6.

Table 2. Reverberation time and sound propagation results before and after the intervention measured according to ISO 3382-2 and ISO 3382-3. Data from one measurement position presented.

	Before	After	Δ	Target
$T_{20,mid}$[s]	0.66	0.62	6.1%	A/V≥0.2
$D_{2,S}$[dBA]	3.77	4	-0.27 dB	Highest

5.3 Sound level monitoring

The average noise levels recorded are similar before and after the renovation due to the fact that the noise levels in the space were moderate-low at 56-55 dBA during the day and 49-52 dBA at night (with $L_{S1}>L_{S2}$, S1 and S2 being the locations of the monitor as shown in Figure1). Background noise was fairly high (NC45) due to the HVAC systems in the space being at full capacity (the project was carried out in Barcelona in the month of August). Nevertheless, a slight improvement (i.e. reduction) in sound levels is reflected in the nursing control area after the ceiling replacement (cf. Table 3). It can be concluded that the new ceiling, with a higher absorption class than the old one, is more effective the higher the noise levels are. It should also be pointed out that the corridor under study is located at a hospitalisation area of a post-surgery coronary unit, thus noise levels being somewhat moderate due to the nature of the patients hosted there and also the staff controlling at all times the noise produced.

Table 3. Results of the monitoring of sound levels measured in the nursing area (marked as S1 in Fig.1).

	Before	After	Δ
$L_{Aeq*,day}$(dB)	56.5	55.8	-0.7 dB
$L_{Aeq*,night}$(dB)	49	48	-1 dB

5.4 STI measurements (IEC 60268-16)

STI measurements at different locations from the source were carried out, the results being shown in Figure 6. A slight improvement (i.e. decrease in STI/intelligibility) is depicted, due to the attenuation of sound propagation the new ceiling has provided.

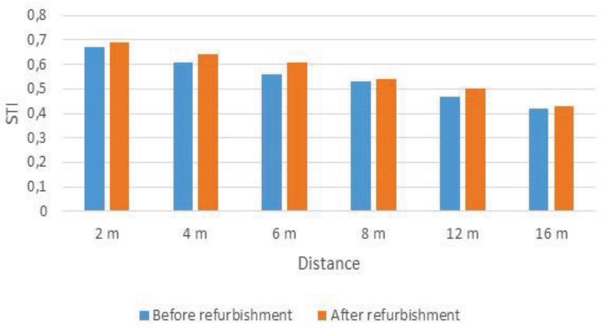

Figure 6. Comparison of the STI measured at different positions along the corridor both before and after the refurbishment, with the sound source located by the nursery station at S1 (cf. Figure 1).

Without obstacles, RT decreases with increasing STI. On the contrary, if the STI goes down (without hindrance), it means the RT has gone up. The latter is not optimal in cases where RT is not low enough; however in cases where RT is slightly higher like the one under study, it becomes a compromise between privacy (i.e. sound propagation) and noise levels. Noise barriers such as sliding glass doors (if possible) and wall panels could help lessening propagation.

5.5 Subjective evaluations

An unstructured series of interviews were carried out with both staff of the coronary unit as well as the maintenance and infrastructure department of the hospital. Hereunder, some quotes from the interviews are given:

- Eduardo Martínez (vice-director of maintenance and infrastructure): *“we decided to undergo a renovation of the corridor - mainly refurbishing the ceilings- due to the fact that the previous ceiling was very damaged, and aesthetically speaking horrible. The result was fantastic: the Ecophon Access is a very beautiful as well as an operational and practical ceiling. One can really notice the acoustic difference”*.
- Adela Amat (head nurse at the transplant department of Vall d’Hebron: *“After the refurbishment of this unit, where the new ceiling was installed, we quickly noted that the mechanical noise coming from trolleys transporting clothes and medical material was highly damped, which in turn helps improving the rest of patients during the night. On top of that, the ceiling also gave spaciousness and luminosity to the unit. It is much more modern and the white colour gives a spaciousness feeling”*.

Even if the results the acoustic measurements yielded were not strikingly better than prior to the renovation, the reality is that the subjective perception of end-users, evaluated through unstructured interviews, was markedly better. The latter highlights that sometimes small marginals in the paper can lead to huge improvements.

6. SIMULATIONS

In the following section, simulations aiming at comparing different acoustic treatments and finding solutions enabling more comfort for end-users were performed using the commercial software Odeon. More specifically, a parametric study with the objective of comparing relative differences between simulated cases rather than matching absolute values was carried out.

6.1 Effect of wall panels in reverberation time

In Figure 7, the 3D model is depicted. Acoustic wall panels (absorption class A) of dimensions 1.2x1.2 m^2 class A. The standardised sound source was modelled following ISO recommendations, and several evaluation points were considered along the corridor (cf. Figure 7).

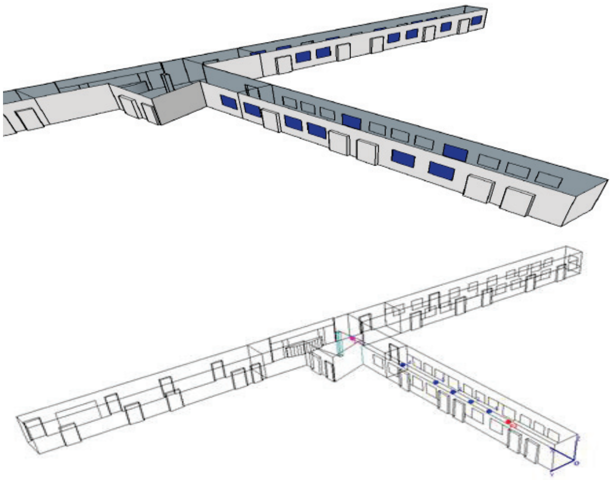

Figure 7. 3D model of the corridor. Class A acoustic wall panels are shown in blue colour (upper picture). In the lower picture, the Odeon model is shown with noise sources and receiver positions indicated (in red and blue colour respectively).

Table 3. Simulated RT with wall panels installed and noise source in position S1 (as per Figure 1).

Sour-dist.[m]	T_{20} [s]						T_{mid} [s]
	125	250	500	1k	2k	4k	
2.4 & 6	0.6	0.46	0.46	0.46	0.45	0.43	0.46

When installing both ceiling and wall panels, the RT drops significantly compared to the measured RT. This may be due to the increased absorption, but above all due to the placement of this absorption on and along the lateral walls. It should be noted that the aim here should not be to just reduce as much as possible the RT (0.5-0.6 s. would probably be an aceptable target value as pointed out in some National regulations, cf. Section 2). Instead, eliminating potential flutter echoes or annoying reflections could be equally important. To that end, strategic placement of wall panels is crucial. On top of that and aiming at reducing sound propagation, some strategies used in open plan offices (such as screens, dividing spaces, sliding glass doors…) could be effective; however in hospitals this could not be viable due to functional requirements.

7. DISCUSSION

Although a corridor may seem a simple morphology of space to study, its geometry and the fact that the analyses were done with the hospital under operation (i.e. not having total control over the environment), made that several discrepancies with what could be expected arose. The authors would like to point out the following issues/findings during the course of the work:

- The corridor under study was not in a highly trafficked area, i.e. the effectiveness of a more absorbent ceiling being installed was not as obvious as it could have been expected beforehand. As a matter of fact, as pointed out in Section 5.3, the new Class A ceiling performed better the higher the noise levels were in the space i.e. by the nursery station vs. in the middle of the corridor (also because it is a narrow space with strong presence of lateral reflections).
- The existing ceiling before refurbishment was already acoustic (Class C at least), most likely with further improved absorption due to a thick layer of dust accumulated in the plenum and installations thermally insulated running on top of it (observed via visual inspection). That could be another reason for the results not differing that much before and after the renovation as it could have been expected by experience.
- The installations running over the new ceiling after renovation (more packed than before) may make the Ecophon Access Class A ceiling not behave acoustically as shown in Table 1. In fact, almost no air cavity in the plenum was available after the renovation (cf. Fig.8).
- In line with the previous comment, the plenum after renovation is 450 mm, larger than the existing one of 200 mm used during the acoustic test results shown in Table 2, which has surely modified the acoustic properties of the ceiling too. The effect of what is in the cavity is more distinct in narrow spaces with little ceiling (i.e. absorbing) surface compared to the reflective ones.
- Due to the latter (hospital under operation, existing installations on top, larger ods…) no acoustic product would behave in the same way as it is shown by lab measurements, making it also hard to create a calibrated computer model to further investigate potential improvements.

All the latter made the results not being directly comparable, although both objective parameters as well as subjective experiences do show an improvement for the end-users using the space daily. More attention to these spaces, which could seem trivial should be paid, since they can be tricky and challenging acoustically.

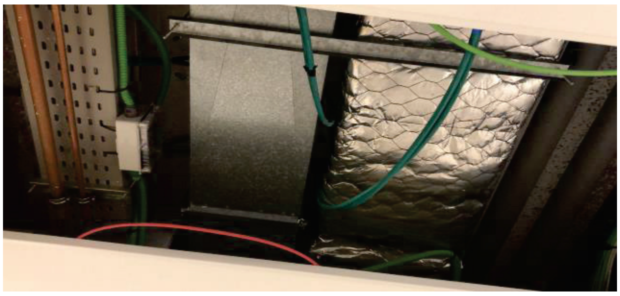

Figure 8. Installations running over the new ceiling.

8. CONCLUSIONS

Inadequate acoustics will lead to errors and, in the long term, lack of privacy, comfort and could thus potentially have a negative impact on both patients and staff. Hospitals operate 24 hours a day and some of the corridors are likely to be busy both day and night. Due to the latter, it should be ensured, through proper acoustic design (space morphology, sound absorbing ceilings with a Class A absorption, Articulation Class larger than 180, sound absorbing wall panels...) that sound propagation and noise levels are adequate, favouring privacy and comfort. In the study presented in this paper, an acoustic refurbishment of a hospital corridor of a coronary unit in the Hospital Vall d'Hebron in Barcelona was carried out. Acoustics measurements of several parameters were performed both before and after the renovation. The results showed that the installation of a Class A absorbing ceiling, with higher absorption than the old one, brought along slight improvements in reverberation time (especially at certain frequencies), noise levels and sound propagation. The slight improvements in the paper showed to be more perceptible by the users (evaluated through unstructured interviews) than it could have been anticipated, this showing that sometimes small marginals in the paper can lead to huge subjective improvements. Moreover, the effect of other acoustic treatments not included in the real project of the corridor (e.g. acoustic wall panels) was evaluated by means of simulations. Last but not least, on top of the obvious acoustic benefits good room acoustics can bring to staff and patients, the "side-effects" a "proper" acoustic ceiling can contribute with for the end-users (staff and patients) in terms of aesthetics, indoor air quality, luminosity, sustainability… are of paramount importance for their wellbeing.

9. ACKNOWLEDGMENTS

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