DESIGN CONSIDERATIONS FOR IMPROVEMENT OF SPEECH INTELLIGIBILITY AND PRIVACY IN A HOSPITAL INTENSIVE CARE UNIT

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Acoustics problems that mainly occur in an ICU are noises from medical staff activities and equipment. Excessive sound from human conversation is considered as unwanted noise. Activities within the ICU requires the staff movements, which also creates non-stationary conversation area especially near the patient's bed. Despite of this condition, nurse station is the location where the noise produced from conversation will raise significantly and where lack of speech privacy becomes a concern and higher chance of less confidentiality of medical information. The research is based on computer modeling that enables inclusion of scattering effects. By principle, the acoustical treatment in a nurse station is to avoid speech leakage from this area as well as to improve the speech intelligibility. Several improvement ideas is by installing hanging abfussor at the nurse station, hanging abfussor near the patient bed, and a glass partition at the nurse station. The speech privacy distance (r_P) and distraction distance (r_D) can be predicted using ISO 3328-3:2012 method and %Alcons formula based on the STI values. To evaluate the effectiveness of the improvement, an auralization scenario of the activities within the ICU is used in a survey. All the improvement design proposed did not create significant impact to the acoustic quality based on the r_P and r_D values. However, this paper demonstrates a good technique to predict the range of easiness of nurses' communication in their workspace while they continuously move. It is given by the distraction distance that is used here to predict speech intelligibility of certain source to receiver distance. The result is a guideline for nurse station design optimization using three design approaches above by utilizing abfussor (absorber and diffuser) as part of the building interior.

Keywords: hospital, speech privacy distance, distraction distance, STI, %Alcons

1. Introduction

Hospital is a commercial building that plays an important role in supporting the health quality of a community. Its occurrence and service should not consider the functionality aspect only but also the occupants comfort including the medical staffs. Acoustical comfort is one of the significant building performance indicator. It is important since activities within the hospital require a quick reaction and mobility from the health workforce without creating discomfort inpatient condition. Besides that, in each area of the hospital requires a certain acoustical conditions that varies from section to section or zone to zone. For example, at the receptionist area, speech intelligibility is required meanwhile, speech privacy is mostly recommended for inpatient area.

There are several type of inpatient facilities in a hospital. Each serves a specific function. The Intensive Care Unit (ICU) provides the highest rank of medical treatment for patients with critical condition [1]. To engineer the acoustical condition is most likely needed since spaces for the patients are connected and could be considered similar to an open plan office working area.

Several publications about the acoustic conditions of health facilities and its effect to the occupancy comfort have triggered the need for further investigation [2,3]. Several researches have shown that in almost every hospital throughout the world, the sound intensity has increased quite high in each year. Within the last 45 years, there has been an increase of 15 dB, with the background noise level around 46 dB to 68dB. An increase of 15 dB is an unideal condition. This also occurs in ICU with a background noise level around 62 dB to 68 dB, with the noise source coming from medical equipment and their supporting installation.

A research in John Hopkins hospital has found that noise exposure can threaten the medical staff health, distract working performance, create stress that triggers anger, hearing impairment, and change the psychosocial environment [4]. Medical staffs admitted that the high noise level in their working environment are often the most annoying working condition. The negative effect may increase emotional level and depression which furthermore, created errors in the medical treatment.

A standardized noise limit in Indonesia's hospital has been issued by the Ministry of Health no. 48 1996 [5]. For ICU, the maximum noise exposure is 40dBA. In the Guidelines for Community Noise WHO, the equivalent sound pressure level (L_{eq}) should not exceed 35dBA for every patient's room or treatment rooms [6]. Related to distraction in communication, for a receiver at a distance 1 m from the speaker, normal conversation can be understood 100% if the background noise is around 35dBA and mostly understood in a background noise level of 45dBA. The American Institute of Architects (AIA) Academy of Architects for Health provides a design guideline for hospital building constructor to support standard of noise control and speech privacy based on regulation from the Health Information Portability and Accountability Act (HIPAA) [7,8]. Noise control enables to reduce errors in medical treatments while a high speech privacy reduce the potency of confidential information leakage. There exist several comprehensive standardized design guidelines for noise control and room acoustics of hospitals, which also covers acoustics privacy [8,9,10,11,12,13].

2. Acoustics problem in ICU

Based on previous researches, excessive noise and unwanted sound are two most common acoustics problem in patient room including in the ICU. In the research in John Hopkins [14] these acoustic problems can threaten the medical staff health as well as the patient. However, in the researches specific to ICUs, the excessive noises are found mostly coming from medical equipment that are used to support the patient's medical treatment. Therefore, referred to the subjective evaluation results, the excessive noise from medical equipment are found to be as wanted sound even though with high SPL values. From the medical staff point of view, this excessive noise is no longer a problem. However, a high background noise level reduces the speech intelligibility and therefore, potential to create medical errors during the medical treatment. Controlling the excessive noise will increase the speech intelligibility but on the other hand, the confidentiality of medical information that should only be heard by certain people inside the ICU that is required may not be fulfil. The working condition supported by the acoustical condition in an ICU is then similar to the problems occurring in open plan offices. Speech privacy and distraction to work caused by speech activities are the issues that will be discuss in this paper. The ISO 3382-3: 2012 is used as the method approach to predict the speech privacy distance and distraction distance based on STI's values.

3. Parameters

To predict the speech privacy distance (r_P) and the distraction distance (r_D), the speech transmission index (STI) values of each measurement position for a certain source position are needed. Values were obtained using measurement procedure described in the ISO 3382:3-2012: Acoustics-Measurement of room acoustic parameters part 3: Open plan offices. Discussion on how to calculated and obtain STI is provided in many references and will not be provided in this paper. Two parameters explained are r_P and r_D.

3.1 Privacy Distance (r_P) and Distraction Distance (r_D)

Privacy distance is the distance that represents a private speaking condition between two or more persons, from an unwanted listener position. The third party is not expected to understand nor even to hear any of the conversation. In the ISO 3382-3:2012 it is mentioned that a good acoustic condition is if the distraction distance is less than ≤ 5 m and a poor condition is a distraction distance more than 10 m. Distraction distance is the distance that represent a condition where a third party is experiencing working distraction due to conversation between two or more other people. In many cases, the privacy distance can only be determined through extrapolation and the dimension might be larger the dimension of the room. In this case distraction distance becomes more relevant to be used [15].

In the ICU, hypothetically privacy is no longer an issue since occupants are only medical staff and the patients in ICU are patients with severe and mostly in unconscious conditions. The distraction distance in the ICU indicates a different acoustic condition with r_D in open plan office. In the ICU, nurses will work as a team where ideally, all the nurses should be alert to all the patient condition. The farther the nurses can communicate clearly, the more effective the team work is. Therefore, a large distraction distance is wanted.

3.2 %Alcons to predict r_P and r_D

This method is to calculate the predicted r_P and r_D for a given receiver and source position. During their activities in the ICU, the nurse keep on moving but mostly will perform their work near the patient bed. Therefore, the r_P and r_D for nurses speaking near a patient bed should be predicted and also for nurses at the nurse station. This method with $\%Al_{cons}$ requires the reverberation time (T_{60}) and STI values for each receiver position with a given source. Distance of source to receivers are also important.

The steps to obtain the r_P and r_D can be described as follow. First we recall Eq. 1 for %Alcons.

$$\%Al_{cons} = (170{,}5405)\ e^{(-5{,}4119\times STI)} \tag{1}$$

Here we need to input the STI value for that position and the %Alcons will be obtained. Another %Alcons formula is then used as shown in Eq. 2

$$\%Al_{cons} = \frac{200r^2{T_{60}}^2(1+n)}{VQM} \tag{2}$$

Where r is the source to receiver distance, T_{60} is the reverberation time, and n is the amount of source. Meanwhile, V is the room volume.

The QM is an unknown variable defined by the source directivity and acoustic treatment of the room. This unknown variable can be obtained using Eq. 2 by substituting the %Alcons value obtained from Eq. 1. Referring to the ISO 3328-3:2012, the STI value for ideal speech privacy distance is 0.2 and 0.5 for ideal distraction distance. These STI are then substituted into Eq.1 and we obtained the %Alcons privacy and %Alcons distraction.

$$\%Al_{cons}privacy = (170{,}5405)\ e^{(-5{,}4119\times STI)}$$

$$\%Al_{cons}privacy = (170{,}5405)\ e^{(-5{,}4119\times 0{,}2)}$$

$$\%Al_{cons}privacy = 57.7$$

Similar to the steps above, %Alcons distraction can be obtained.

$$\%Al_{cons}distraction = 11.39$$

We use again Eq. 2 and the QM value obtained previously at that measurement point. For each receiver will have a different QM values. Meanwhile, V and n are the same. At this step, r is no longer the source to receiver position but it is the speech privacy distance or distraction distance of interest. If we want to calculate r_P then $\%Al_{cons}privacy = 57.7$ is used and for distraction distance we use $\%Al_{cons}distraction = 57.7$.

4. Methodology

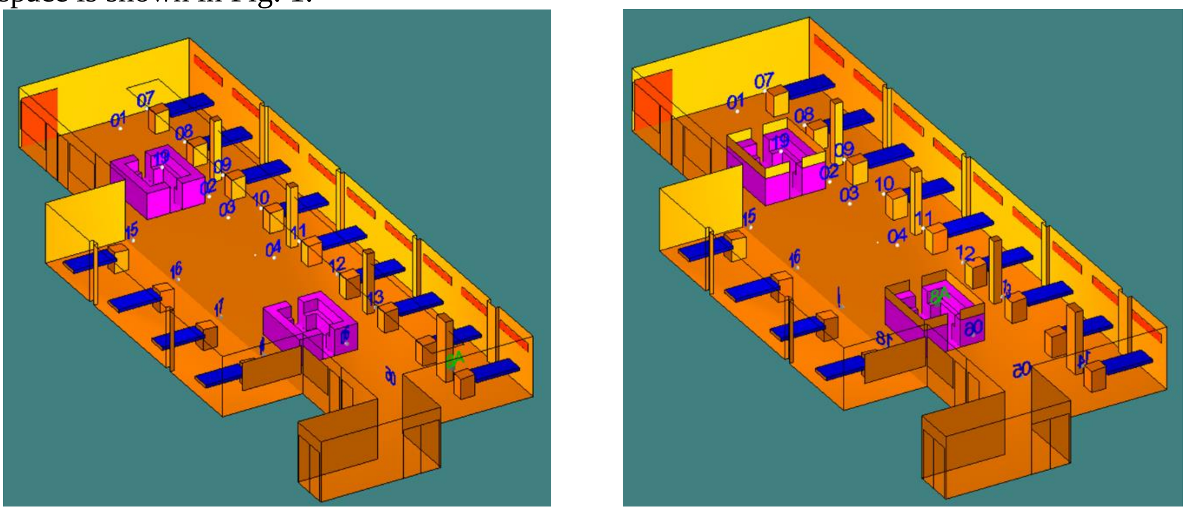
In the ISO 3382-3:2012 Acoustics-Measurement of room acoustic parameters part 3: Open plan offices, techniques on how to measure the acoustical performances of an open-plan office is described and were adopted in the ICU measurement using computer simulation. Example of measurement using this standard measurement is provided in other publication [16, 17, 18]. As for the privacy distance and distraction distance, there is a cut off STI values that defines if the room is private for conversation (STI $\leq$ 0.2) and if distraction occurs within the room (STI $\leq$ 0.5). In order to find the r_P and r_D for a room, using this technique, measurement of the STI at several distances with receivers positioned in a straight line is required. A regression is then computed using the STI's and the distances of receiver to source. Privacy distance (r_P) is obtained using this regression model by setting the STI values (variable x in the regression model) as 0.2. Meanwhile, for r_D, the STI is set as 0.5.

In many cases the r_P and r_D exceeded the farthest room boundaries and therefore, it can be concluded that in this room there is no speech privacy and all the communication activities that occur is distracting for the workers. However, there will be a case that a certain position actually is private with no distraction and this distance is interesting to be predicted.

As for the case of ICU, there are certain position where the nurse spends most of the time during performing medical treatment. The first position is at the nurse station and second is near the patient bed. Using the approach above with ISO 3382-3:2012, the r_P and r_D are predicted for existing condition and after acoustical treatment is given into the room utilizing computer simulation with CATT-acoustics software.

4.1 Modeling of the existing condition

An ICU of a hospital in Jakarta, Indonesia is used as the model. This ICU has also been used in other publication where on-site measurement was done using soundscape method [16]. Layout of the space is shown in Fig. 1.



(a) (b)

Figure 1: Layout of the ICU used as the case studied (a) source near patient bed, labelled as source I, and (b) source at nurse station, labelled as source II

4.1.1 Source position

There are two source positions, one at the nurse station and second is near the patient bed, with constrains due to the bed position and measurement rules in order to comply with the ISO 3382-3:2012. An omnidirectional source with an output level of 94dB is used, positioned at a height of 1,6 m above the floor, and 2 m from the side walls. In Fig 1. the source is indicated by the green ‘ID’.

4.1.2 Receiver position

According to ISO 3382-3:2012, receivers should be placed on an imaginary straight line with a certain distance apart in order to obtain the regression model of STI values and distances. There are two position scenarios. The source and receivers’ position is shown in Fig. 1.

4.2 Modelling with Acoustic Treatment

The acoustic treatment is basically applying abfussor on the ceiling at two different position and adding partition at the nurse station side boundaries. Abfussor is a term for acoustic panel that can behave as both an absorber and diffuser. This treatment is chosen since the intention is to reduce excessive noise while reflecting the wanted sound (speech) to a certain direction that is towards the nurse station area only. Abfussor is using the one provided in the CATT-acoustics material database with properties shown in Fig. 2.

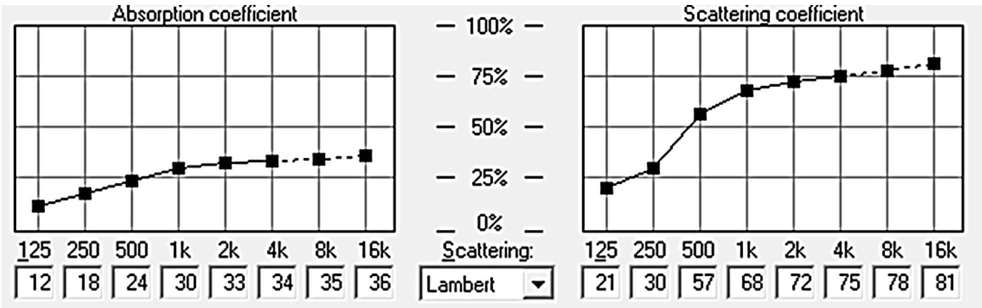


Figure 2: Detail properties of Abfussor using database in CATT-acoustics

There are three treatment models, which are abfussor hanging from the ceiling near the patient bed, abfussor hanging from the ceiling of the nurse station, and glass partition at nurse station. In the first model, abfussor with a width of 1,6 m (common modular size is 0,8 m) are hanging from the ceiling 2,5 m above the floor and located at 1 m from the patient’s bed, expanded from one side to the other side of the ICU (length of 26,4m). The second model has abfussor hanging from the ceiling of the nurse station with a width of 4,2 m x 3,9 m, hanging 2,5 m above the floor. Vertical glass panels with common absorption coefficient for glass are used as the nurse station’s partition. The nurse station desk has a height of 1,3 m and in total with the glass partition, the height is 1,8 m.

4.3 Subjective Evaluation with Online Survey

The subjective evaluation is intended to observe if there is any audial differences due to the acoustical treatment. Values of objective parameters are only slightly different from baseline model and from models with treatments. The result will be provided later with the discussion. Therefore, results from the subjective evaluation might support the evidence. An online survey using Survey-Monkey© was conducted with 2 parts. Part I consists of questions related to the respondents identi-ty and listening ability (age, gender, potential of hearing impairment). Part II consists of 18 ques-tions linked to 6 stimulus. The questions are comparing pairs of stimulus of its clarity, reverberant, and loudness.

5. Results and Discussion

This research is using a mix-method by measurement of objective parameters and conducted a subjective evaluation. However, these objective and subjective parameters are not yet correlated for the analysis. It is used to provide indication whether or not the acoustic treatment in the ICU created different results of objective parameters and different audial experience.

5.1 Predicted Speech Privacy Distance and Distraction Distance

There are two types of predicted r_P and r_D measured. One is the room r_P and r_D obtained from linear regression of STI to distance based on ISO 3382-3:2012. The other r_P and r_D are obtained using the %Alcons method for each receiver. This predicted r_P and r_D is important since in the ICU, the human speaker (source) and the listeners are very mobile, scenarios of source to receiver distance can be very random. In most cases, the source and listeners might not be positioned in a straight line. The results are shown in Table 1 for four modelling scenarios, which are baseline (A), model with abfussor hanging from ceiling near patient bed (B), model with abfussor hanging from nurse station's ceiling (model C), and model with glass partition at nurse station (model D). In this research, two source positions were observed as shown in Fig. 1 but r_P and r_D can be predicted using ISO 3382-3:2012 if the receivers are inline on a straight line. Therefore, results are only from experiment setting of Fig.1 (a), which for source I.

Table 1: Predicted r_P and r_D using regression of STI and distance based on ISO 3382-3:2012 and using calculation with %Alcons, for source I.

r_P using ISO 3328-3:2012 for baseline (model A)								34.01
r_P using ISO 3328-3:2012 for Abfussor hanging from ceiling near patient bed (model B)								26.48
r_D using ISO 3328-3:2012 for baseline (model A)								4.01
r_D using ISO 3328-3:2012 for Abfussor hanging from ceiling near patient bed (model B)								3.88
	Recievers 'ID'							
	6	7	8	9	10	11	12	13
r_P (A)	16.63	63.09	52.30	47.32	42.90	38.12	31.01	25.67
r_P (B)	16.63	52.20	44.46	41.33	37.47	34.21	27.83	25.67
r_D (A)	7.38	28.02	23.22	21.01	19.05	16.93	13.77	11.40
r_D (B)	7.38	23.18	19.74	18.35	16.64	15.19	12.36	11.40

Results in Table 1 indicated that there are slightly any difference of the r_D between the baseline (existing condition) and having acoustic treatment. Using the open office acoustics quality index the r_D less than 5 m for both conditions, indicated that the ICU have a good acoustics quality.

Figure 3 is an illustration of the r_P for all the four models, using receiver number 6 and source II. Meanwhile, Figure 4 is for distraction distance (r_D). Using this visualization graphic of the predicted r_P and r_D, it is shown that the treatment created only slightly change to the distances by less than 0,30m.

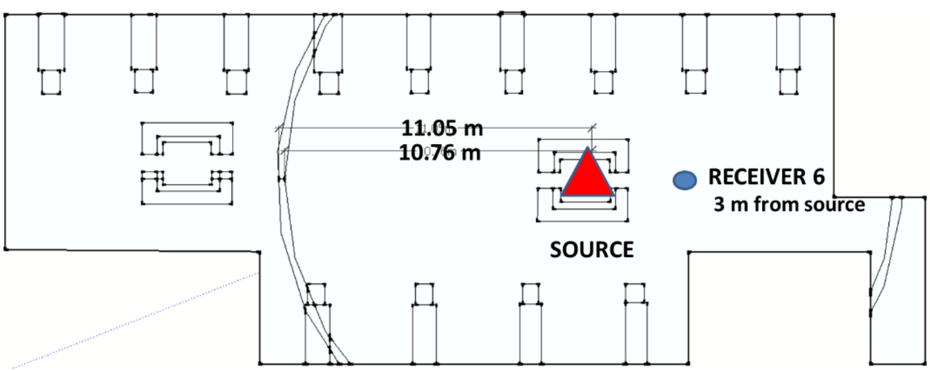


Figure 3: Privacy distance (r_P) of baseline and model B, using source II and receiver number 6.

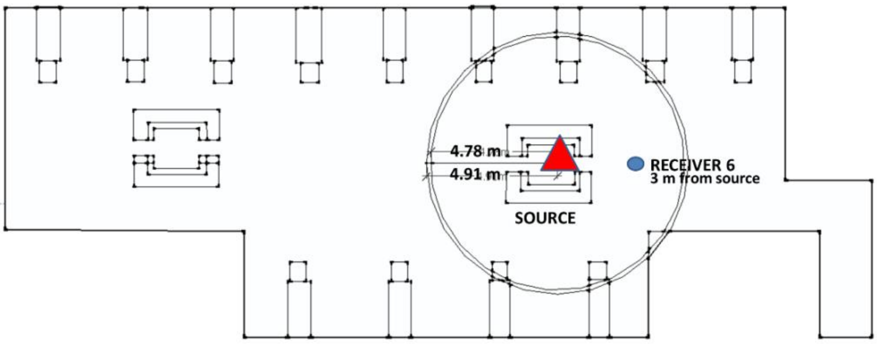
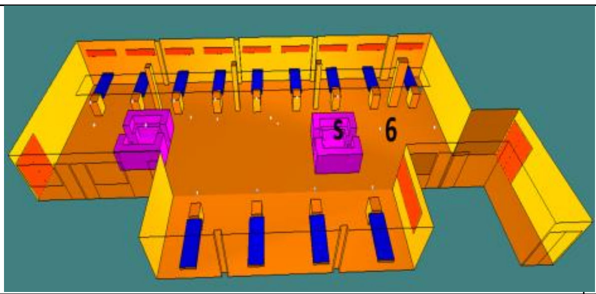
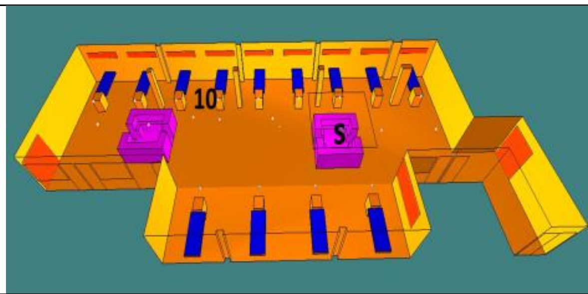


Figure 4: Distraction distance (r_D) of baseline and model B, using source II and receiver number 6.

5.2 Subjective Evaluation

Respondents that registered to the survey online are 173 person. Among them only 95 person (55%) did a complete survey. Results of the survey are provided in charts shown in Figure 5. The poor association between the objective parameters and subjective evaluation for all stimulus comparison are indicating that there are no difference in the audial experience for all four models with different acoustic treatment. All stimulus comparison means all comparison of the model with acoustic treatment to the baseline, for example, auralization in model A compared to model B, auralization in model A compared to model C, etc.





Question	1	2	Question	1	2
Which one sounds clearer? **C_{50} of 1 > C_{50} of 2**	44%	56%	Which one sounds clearer? **C_{50} of 1 = C_{50} of 2**	51%	49%
Which one sounds livelier? **T_{30} of 1 < T_{30} of 2**	60%	40%	Which one sounds livelier? **T_{30} of 1 < T_{30} of 2**	49%	51%
Which one sounds louder? **Total SPL of 1 < Total SPL of 2**	83%	17%	Which one sounds louder? **Total SPL of 1< Total SPL of 2**	75%	25%

Figure 5: The online survey result for source II and receiver no 6 and 10 with stimulus comparing auralization in model A (baseline) and model C (abfussor on nurse station's ceiling)

6. Conclusion

Techniques to predict the speech privacy and distraction in an ICU as a working space referring to the ISO 3382-3: 2012 Acoustics-Measurement of room acoustic parameters part 3: Open plan offices is provided in this paper. Hypothetical acoustics problem is that in the past excessive noise is found in the ICU. However, is it not a problem for the nurses since it is mostly wanted noise coming from medical equipment to monitor patient's condition. The high background noise level might reduce the speech intelligibility and therefore, potential to create medical errors during the medical treatment while confidentiality of medical information is also important. Thus the acoustical problem becomes similar to conditions in open plan offices.

The r_P and r_D calculated using ISO 3382-3: 2012 based on STI's values produced from computer simulation, is indicating that the ICU observed has a good acoustics quality for communication in office where all the r_D is less than 5m. However, r_D in the case of ICU is in contrary. It is expected to be large for ICU in order for nurse positioned at other side to be able to hear the conversation.

This will lead to a quick response for all patients laying on every bed. A nurse at the nurse station talking to another nurse in 3 meters apart can only be heard by 3 patient beds nearby the nurse station. In terms of privacy, this supports the need for maintaining confidentiality of medical information.

Design improvement using model B, C, and D did not create significant impact, with changes of r_P and r_D in the range of 0.2 to 0.3 meter. Subjective evaluation also confirms this finding since no association are found between the objective parameters of speech intelligibility, SPL (loudness),C_{50} (clarity for speech), and T30 (reverberation). Among these room models, hanging abfussor at the nurse station ceiling created the most difference from the existing condition (baseline). Further modelling is needed to explore more application of the acoustic treatment on the nurse station ceiling area.

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