Access to daylight and outdoor views: a comparative study for therapeutic daylighting design

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A well-balanced and good visual environment is of major importance to patients' health. But information about the impact of daylight on clinical recovery is necessary in order to effectively assess the need for the modernisation of existing hospitals or to evaluate alternative strategies for new hospital design.

In the search for a relationship between daylight and clinical recovery, an individual's preference to daylight over artificial light has been well established\(^1\),\(^2\). In addition, the relationship between daylight and the psychological benefit\(^3\) for hospital patients, as well as the impact of daylight on specific physical diseases related to bones and cancers (e.g. rickets and skin cancer) are also well researched\(^4\).

However, defined knowledge about the impact of daylight on general diseases, such as diseases originating from the malfunction of organs such as the heart, lungs, stomach and kidneys and not generated from psychological pressure, is weak and studies are few in number\(^5\), provide controversial findings\(^6\) and are debated\(^7,\)^\(^8\).

To implement daylight strategies within the therapeutic design of hospital buildings, the impact of daylight on general diseases needs to be better established with sound evidence.

The objective of this paper is to find an evidence-based relationship between daylight, outdoor view and patients' recovery rate in a general hospital environment.

**Methodology**

While the effects of daylight on different diseases and patients in the therapeutic environment have been analysed in previous research, the more intensive studies appear to have focused on surgical patients\(^9,\)^\(^1\)\(^1\)^\(^1\). In most cases, surgical patients have to undergo a standard procedure of treatment before and after surgery and are in a near equal state of physical condition after the same surgery when they come back to the ward from post-operative care units.

Therefore, it was decided that a number of patients who had undergone a major open-heart surgery would be used as samples for this study. After surgery, patients are moved to a bed in the cardiac surgical intensive care unit. Once they have improved to a satisfactory level and were moved to rooms in the cardiac surgery unit, they were used for the observational study.

To build a reliable model for this study, the following criteria for sample selection were fixed:

- Selection of a uniform patient population for sampling (e.g. patients undergoing a particular type of surgery/procedure or very specific patient group).
- The sample should not consist of a particular disease or a whole ward, where the physical problem is the same but complication levels
mean that clinical recovery or patients’ length of stay may differ:
• Selected samples should be in an equal or nearly equal stage of the disease at the beginning of the study.
• The patients should be free from other major complexities.
• It should be a non-psychological disease and not be related to bones or cancer (as the relationships with these diseases have already been established).
• The disease should cause both physical and psychological stress to patients.
• To recover, all patients should undergo a standard procedure of treatment.
• The patients must have to stay in hospital for several days to undergo treatment, so that the investigator has enough time to observe their progress before release.

In general, variables can be grouped into four major classes: environmental, physiological/clinical, demographic and psychological. Clinicians tend to focus more on clinical variables while non-clinicians focus on environmental or architectural variables. However, there are some common variables selected by both groups. Reviewing past works on variable selection, the following variables are recommended for further research for this study:
• environmental variables: illuminance (average daylight intensity in lux), temperature, relative humidity (RH), room type (single/double bed) and provision of outdoor view (POV);
• clinical variables: length of hospitalisation, blood pressure, temperature, heart rate, respiratory rate. Following discussion with hospital medical staff, a number of other variables were also identified: smoking habits, hypertension, dyslipidaemia, myocardial infarction (MI), transient ischaemic attack (TIA), stroke, bronchial asthma, cerebral vascular diseases (CVD), diabetes mellitus (DM), chronic renal failure (CRF), ejection fraction value (EF), pulse oximeter arterial haemoglobin oxygen saturation (SPO2), fasting blood sugar (FBS) and fluid balance;
• demographic variables: gender, age, weight, body mass index (BMI), etc;
• psychological variables: as psychological variables are correlated with clinical variables, the direct and indirect psychological impact of daylight on patients’ physical health can be observed by analysing the clinical variables mentioned above. To make the research more objective and avoid multicollinearity between variables, emphasis was given to the parameters of patients’ physical health indicators and no psychological variables were recommended separately.

Statistical model
To fill the research gap, an evidence-based relationship needs to be developed which can correlate daylight intensity with clinical variables (blood pressure, temperature, heart rate, respiratory rate, etc) to predict patients’ stay time.

Based on a critical review of key pieces of research relating to the therapeutic effects of hospital building and lighting\(^{2,9,10,12,13}\), a multiple linear regression model (MLR) was developed using stepwise regression to finalise the environmental and clinical variables, and to correlate these two groups of variables. MLR attempts to model the relationship between two or more explanatory (independent) variables and a response (dependent) variable by fitting a linear equation to observed data. Every value of the independent variable ‘x’ is associated with a value of the dependent variable ‘y’. Formally, the model for multiple linear regression for ‘n’ observations, is:

\[
y = a + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + b_5x_5 + 
  b_6x_6 + b_7x_7 + \ldots + b_nx_n + e
\]

where, \(y\) is the true dependent, ‘a’ is the constant or intercept, the ‘b’s’ are the regression coefficients for the corresponding ‘x’ (independent) terms, and ‘e’ is the error term reflected in the residuals. It should be noted that, whether it is for a single variable or for multiple variables, the relationship predicted is always linear. In the least-squares model, the best-fitting line for the observed data is calculated by minimising the sum of the squares of the vertical deviations from each data point to the line (if a point lies on the fitted line exactly, then its vertical deviation is 0). Because the deviations are first squared, then summed, there are no cancellations between positive and negative values. The ordinary least-squares estimates \(b_1, b_2, b_3, \ldots, b_n\), are usually computed by statistical software packages (e.g. SPSS).

For this study, the dependent variable of the model \(y\) was the recovery time of each patient in the hospital room in hour and the explanatory variables \(x\)’s) were comprised of the rest of the environmental, clinical and demographic variables. The number of explanatory variables could then be eliminated step by step to develop a suitable statistical model.

Measurement of daylight
One of the constraints of daylight research is the estimation of daylight levels which change rapidly with the change of cloud cover in the sky over time\(^{14,15}\). In Walch et al’s research\(^9\), the measurements of sunlight intensity were taken by a light meter twice daily in the observed patients’ rooms at approximately 9:30am and 3:30pm. These were multiplied by the number of AM and PM daylight
exposure hours and summed to determine the cumulative daily sunlight exposure in lux-hours. However, the measurement of sunlight intensity twice daily does not adequately represent the actual daylight levels that the patients experienced during their stay time in hospital because of the rapid change of daylight intensity throughout the day. A more continuous measurement of sunlight intensity for patients’ rooms is necessary for reliable results. This can be done by either installing several data loggers in each patient room or using simulation software to find out the average daylight levels. As it is not possible and practical to fix several data loggers on the work plane of the each patient’s room to measure illumination in a running hospital environment, the application of a daylight simulation programme was recommended for the study.

To analyse the daylighting environment, Choi used a lighting simulation program, ‘Radiance’, to test the illuminance level in his study. To verify the output data from Radiance, the calculated data produced by Radiance were compared with the data from measurements taken at the site and using the scale model. The discrepancy between Radiance and the on-site measurements was 2% to 47% and Radiance and the scale model was 9% to 50%. Choi suggested that, as daylight is very much sensitive to sky conditions, it can result in large discrepancies, due to the differences between CIE sky conditions (defined by International Commission on Illumination (CIE)) and the actual sky conditions. For example, CIE’s intermediate sky condition does not cover varying amounts of cloud in the sky and is therefore not the same as actual sky condition. Thus, the horizontal exterior illuminance (HEI) of Radiance is not identical to actual HEI values. One HEI value cannot cover the diversity of the intermediate sky which has 30% to 70% of the sky covered with clouds.

Figure 1 shows the variation of average HEI from 19 November 2008 to 21 January 2009 for Dhaka, Bangladesh. For this study, one outdoor data logger (UA-002-64, pendant logger temp/light, 64k memory) was installed at the top of the helipad, above the hospital roof, about 66 metres from ground level (Figure 2) to measure HEI at five-minute intervals. The output of the data logger was used to simulate the average interior daylight intensity of the room used in the case study, considering the CIE standard overcast sky model with a full progressive radiosity inter-reflection method using the FlucSDL module of the IES <Virtual Environment 5.5> software package.

Data collection and analysis
The study started on 18 November 2008 and ended on 22 January 2009. Compliance with the Data Protection Act 1998 was ensured and the research was checked by an ethical advisory committee. The hospital authority was informed of the objectives of the research and approval received before the work was started. Participating patients...
signed informed consent forms before being discharged from hospital.

The cardiac inpatient unit, which is located on the tenth floor of the 15-storey Square Hospital building in Dhaka was selected for the observational study. In the layout of the floor plan, the toilets are placed on the corridor side of the patient’s room rather than on the façade side, thus providing scope for ample daylight inclusion from outside (Figure 3). As the location of the unit is on the tenth floor and the majority of the surrounding buildings are six-storey or less (Figure 4), there were few obstructions to daylight from the surroundings. But the actual built surroundings were incorporated during simulation modelling (Figure 6). All rooms were painted in the same colour and were equipped with similar furniture and facilities.

The floor consists of both single- and double-bed rooms. In the double-bed rooms, a 1.8m-high movable screen is used for privacy. As a result, the outdoor view was restricted for the patients who stayed in the inner side beds.

As the focus of the study was to compare patients who had experienced varying daylight intensity during their stay in hospital rooms which also provided outdoor views, the architectural layout and arrangement of the floor was appropriate for the study.

A total number of 278 patients were treated during the study period. They could be grouped in three categories: open-heart surgery patients, patients treated with only medicine and patients who had undergone minor surgery. In line with the criteria set out for the study, 41 open-heart surgery patients were initially selected for observation, as they were considered to be the most uniform patient group of the three categories.

To eliminate bias, the experiment was run double-blind; that is, neither the patients nor the doctors knew about the lighting status of the rooms and the researchers never met the observed patients. During this time, further tests were conducted to assess and monitor the patient’s physical development.

The researchers used the test results for statistical analysis to understand the development of clinical recovery process. Patients’ stay in the cardiac unit usually lasted from two days to a week or longer after they were transferred from the cardiac surgical intensive care unit. The focus of this research was the influence of daylight and POV on patients’ stay time and recovery process.

Of the 41 patients, 33 were coronary artery bypass graft (CABG) surgery patients and the other eight had other types of surgery, such as for coarctation repair, valve replacement, atrial septal defect (ASD) or patch closure. The operations were successful for all 41 patients. One patient who stayed less than 48 hours in the cardiac surgery unit after transfer from the cardiac surgical intensive care unit was excluded from study. The 40 remaining patients, each of whom...
stayed at least 48 hours in the inpatient rooms, were used as the sample for statistical analysis. For each observation, a total of 32 possible explanatory variables were first considered (Table 1). Patients’ clinical and demographic information was collected from hospital records. The environmental variables of the rooms (light, temperature, RH) were collected by installing three indoor data loggers (U12-012, temp/RH/light/ext data logger, 12 bit) in three representative rooms oriented in the north, south and east. Data loggers were fixed on the back wall of patient’s bed above the patient’s head at a 2-metre height from floor level to avoid shadows on the sensor from the movement of patient and hospital staff (Figure 6).

Greater variation was found in lighting intensity for different orientations at the specific point where the data loggers were fixed. However, the variation in temperature and RH was not significant, as the building was centrally air-conditioned. Average illumination values for each patient’s room with respect to the patient’s time in the cardiac surgery unit after surgery were obtained by daylight simulation. Readings of the outdoor data logger were used as the HEI to simulate the average daylight intensity. As-built drawings, specifications and information based on a physical survey of the hospital building were used to generate the 3D-model for the simulation study, as described earlier (Figure 7).

Table 1 presents a sample summary of the statistics of the variables. Column one of the table shows the list of provisional variables for the model. In the sample group there was no case of CRF and TIA, and there was only one case of stroke and bronchial asthma and two cases of CVD. The maximum body temperature of the patients was recorded 99°F (37.22°C) and minimum 98°F (36.67°C) with a mean of 98.05°F (36.69°C) and 0.22 standard deviation. Due to the lack of significant difference in CRF, TIA, stroke, bronchial asthma and body temperature in the sample group, these variables were excluded from the model at the beginning of the analysis.

To determine the multicollinearity between variables that may bias the standard error or generate wrong signs and implausible magnitudes in the coefficients,16 the Pearson correlation for the rest of the variables was analysed. The most significant variables of the correlated variables in the model were selected. For instance, mean arterial pressure (MAP) was significantly correlated with weight, height, BMI, age, gender, systolic blood pressure, diastolic blood pressure, respiratory rate, fluid balance, smoking habits and hypertension and all were dropped from the model. In the next stage, a stepwise regression

![Figure 6 (above): Daylight simulation with a full progressive radiosity inter-reflection method](image-url)
analysis was conducted to select the ‘best’ set of explanatory variables and insignificant variables, such as gender, MI, EF, dyslipidaemia, room type, etc., were eliminated from the model. Finally, two environmental variables and five clinical variables were selected for the MLR model. The final set of variables, their coefficients (B), standardised coefficients (Beta) t-statistics, together with the P-values are shown in Table 2.

Model interpretation
As illustrated in Table 2, using the multiple regression model, it was shown that six variables decrease patients’ length of stay in inpatient unit and only one variable is responsible for increasing stay time (diabetes mellitus). All the selected variables are highly significant in the MLR model (P value range from 0.0 to 0.1). Six variables are equal to or less than a 5% level of significance and one variable (POV) has a 10% level of significance. The column of unstandardised coefficients (B) provides the values for the explanatory variables for the final MLR equation. Expressed in terms of the variables used, the final MLR equation can be written as EQ [1] (see Figure 7).

Therapeutic and intuitive judgment confirmed the validity and practicality of mathematical signs in the model (EQ [1]). A view to the outdoors may help to reduce patients’ length of stay (t=-1.636, P value=0.112). And the reduction of patients’ length of stay with an increase in daylight (t=-1.995, P value=0.055) is in line with the findings of previous research from Ulrich18 and Choi.19 It is evident from the model that daylight is more significant (t=-1.995, P value=0.055) between two room variables: daylight and POV. The coefficient estimates show that, while holding the other explanatory variables constant, POV reduces patients’ length of stay by 13.5 hours on average and by four hours per 100 lux increase in daylight (multiplying B with 100 lux).

One of the objectives of the research was to identify whether daylight or POV has a more significant impact on patients’ recovery time. Comparing the standardised coefficients (Beta) of two room variables, it can be concluded that daylight is more important than POV in relation to the recovery process (Beta -1.995 for daylight to Beta -1.636 for POV). The reason may be that daylight has both a psychological and a physical impact on patients but outer views only have psychological effects.

Therefore, based on the estimated MLR model, it can be concluded from an architectural decision-making perspective that a room with more daylight but a reduced view to the outside is better than a room with a better view but less daylight. Providing high windows and skylights for more daylight in a deep-planned, single-storey hospital building or on the top floors of a multi-storeyed hospital building can be an effective solution in a dense urban context, from a therapeutic point of view.

Medical judgments have also confirmed the validity and practicality of the mathematics of the clinical variables in the model (EQ [1]). During and after open-heart surgery, as a result of the anaesthesia, blood pressure and heart rate is usually reduced from its normal state17 – and the patient’s recovery process accelerates with an increase in blood pressure (t=-5.218, P value=0.0) and heart rate (t=-2.626, P value=0.013) to its normal state. As a result, length of stay in hospital is reduced. It is logical that diabetic patients will take more time than non-diabetic patients to recover (t=4.441, P value=0.0) and an increase in patients’ FBS (t=-4.989, P value=0.0) and SPO2 (t=-1.636, P value=0.112) will accelerate recovery after surgery18,19.

Conclusion
In this paper a methodology was developed to establish an evidence-based relationship between the availability of daylight and patients’ recovery rate in a general hospital environment with the help of a MLR model. A case study involving a limited sample group was used to reach a decision about daylight and outdoor view. The limitations of this study, given the time and other resources required for such a systematic investigation, meant the study population was restricted to patients who had undergone open-heart heart surgery and the sample size was small. However, the most uniform patient group in the unit was selected as a sample for this study and the number of insignificant variables was reduced to overcome the limitations of the sample number.

With an increase in sample size and with a variety of surgical patients, it may be possible to generate a statistically more significant model with greater confidence in the impact of other therapeutic elements on hospital patients. According to Pechacek et al20, predicting actual daylight intensity by

<table>
<thead>
<tr>
<th>Explanatory variables</th>
<th>Un-standardised coefficients (B)</th>
<th>Standardised coefficients (Beta)</th>
<th>t-statistics</th>
<th>P-values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>1086.209</td>
<td>5.029</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>Average daylight intensity of the rooms (lux)</td>
<td>-0.040</td>
<td>-0.245</td>
<td>-1.995</td>
<td>0.055</td>
</tr>
<tr>
<td>Provision of outdoor view (POV)</td>
<td>-13.495</td>
<td>-0.198</td>
<td>-1.636</td>
<td>0.112</td>
</tr>
<tr>
<td>Mean arterial pressure (MAP)</td>
<td>-2.365</td>
<td>-0.748</td>
<td>-5.218</td>
<td>0.00</td>
</tr>
<tr>
<td>Heart rate (HR)</td>
<td>-1.444</td>
<td>-0.333</td>
<td>-2.626</td>
<td>0.013</td>
</tr>
<tr>
<td>Diabetes mellitus (DM)</td>
<td>38.049</td>
<td>0.624</td>
<td>4.441</td>
<td>0.00</td>
</tr>
<tr>
<td>Pulse oximeter arterial haemoglobin oxygen saturation (SPO2)</td>
<td>-5.839</td>
<td>-0.366</td>
<td>-3.052</td>
<td>0.0065</td>
</tr>
<tr>
<td>Fasting blood sugar (FBS)</td>
<td>-10.517</td>
<td>-0.651</td>
<td>-4.989</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Table 2: Multiple regression model for patients’ stay time in cardiac unit. Dependent variables: patients’ stay time in hours; R square=0.591; adjusted R square=0.502; F=6.617(sig=0.0)

Patients’ stay time (hours) = 1086.209 - 0.04 Daylight -13.495 POV - 2.365 MAP - 1.444 HR + 38.049 DM - 5.839 SPO2 - 10.517……………EQ[1]

Figure 7: Final MLR equation, expressed in the terms of the variables used.
simulation is beyond the capabilities of all but the most advanced computer modelling software. The researchers chose to use FlucsDL (from the IES software package) to measure the average lighting intensity of the inpatients’ room. Actual outdoor horizontal exterior illuminance measured by an outdoor data logger from site was used to overcome the unpredictable nature of outdoor daylight intensity due to the rapid change of cloud cover in the sky.

The researchers tried to not only establish the impact of daylight and outdoor view on hospital patients but also to illustrate how this knowledge of outdoor view and daylight potentiality can be incorporated in the architectural decision-making process in critical situations. It is expected that the findings from the evidence-based methodology and the relationship established between daylight, outdoor view and recovery time will help to develop a more robust model to support the evidence-based design of therapeutic daylit hospital buildings.

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