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On the applicability of the laminar flow index when selecting surgical lighting

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Abstract

In modern operating rooms ultraclean air is supplied through the ceiling to prevent bacteria from entering an operating wound and cause infections. Operating lamps can disturb this flow of clean air. In this paper the accuracy of some aspects of the Laminar Flow Index of operating lamps was tested. The disturbance of the airflow was determined for different shapes and sizes of operating lamps in an isothermal situation. To accomplish this, an experimental study and a simulation study of a small room with an operating lamp were performed. The infection risk was found to be proportional to the projected surface area of the lamp. Although different lamp shapes resulted in a distinctly different flow pattern in the room, this did not affect the infection risk in a significant way. Operating lamps with a projected area smaller than 0.1 m^2 do not disturb the airflow at all in this particular setup.

Keywords

Surgical lighting, wound infection, operating room ventilation, experiments, CFD.

1. Introduction

Post operative wound infections are caused by bacteria that enter an operating wound during surgery. Whether a patient develops an infection depends on many factors, including the condition of the patient, the use of antibiotics and the nature and amount of bacteria that enter the operating wound. In the operating room the largest sources of bacteria are the patient and personnel [1].

There are various routes through which bacteria can enter the operating wound. One route is through surface contact, for example via the gloves of the surgeon, the instruments or the implants. This research focuses on the airborne route, where bacteria in the air are deposited directly into the wound or onto instruments or implants. Lidwell [2] indicates that this is an important infection route in orthopedic surgery. Operating room ventilation plays an important role in the prevention of contamination through this airborne route. Therefore operating room ventilation systems normally are equipped with high efficiency particulate absorbing filters (HEPA) in the supply air inlet that will filter bacteria [3].

Two types of ventilation systems are generally used in operating rooms. Mixing systems rely on dilution of bacteria in the air. Clean air enters the room through swirl diffusers or line diffusers and dilutes the bacteria that are released from the persons in the room. The concentration of bacteria in the room is relatively uniform. When sufficient air is supplied, this concentration is reduced to a level that results in an accepted risk level for developing wound infections. Displacement systems on the other hand rely on providing clean air in critical areas without mixing with surrounding air. In this case, clean air enters the room at relative low velocity from one wall or from the ceiling directly above the patient. The bacteria concentration in the room is not uniform and should be lowest near the patient wound and instrument tables. Displacement ventilation is more efficient than mixing ventilation if the clean air can reach the wound area and the instrument tables. [4]

Both mixing and displacement systems are in use in hospitals in Western Europe today. Newly built systems are only equipped with ceiling mounted displacement systems, indicated as laminar downflow systems [5; 6]. As displacement systems rely on the correct air distribution within the room, they are more prone to disturbances than mixing systems. For example, the temperature distribution in the room affects the flow field [3; 7] and some systems use this property to their advantage [8]. Room dimensions and supply velocity play a role as well [9]. Local disturbances, for instance thermal plumes from heat sources [4] objects blocking the flow, or people moving [10] can also have a severe influence on the performance of the system. Various guidelines and regulations exist to aid the design of ventilation systems [11]. In particular, the Swiss and German guidelines [12; 13; 14] describe a method to assess the actual performance of a laminar downflow system in an operating room.

Of the local disturbances, the operating lamp is considered to be a critical factor for proper functioning of laminar downflow systems. Chow [15] showed that the position of the lamp influences the degree of protection the ventilation system provides to the surgical site. In order to be able to differentiate between different lamps on this aspect, Leenemann [16] devised the Laminar Flow Index for surgical lighting (LFI):

$$LFI_{Leenemann} = \frac{P \cdot A}{E^2} \quad (1)$$

Where P is the electrical power used by the lamp [W], A the surface area of the operating lamp perpendicular to the flow [cm^2] and E the Illuminance of the lamp at a distance of 1 meter [klux].

LFI allows for a comparison of different lamp designs with respect to their disturbance of the laminar downflow in an operating room. The mechanisms behind the individual factors in Leenemann's index can be explained; the power used by the lamp relates to the thermal plume, the surface area indicates the physical obstruction and the illuminance values higher lighting levels. Tests of Leenemann's formula have not been found. Nevertheless, it is still in use today [17].

Oostlander [18] expanded the original formula by Leenemann and included a dimensionless shape factor F_s [-] that has to be determined experimentally. Furthermore, additional factors for the quality of light, being the depth of illumination t [m] and the color rendering index R_a [-].

$$LFI_{Oostlander} = \frac{P \cdot A}{E^2} \cdot F_s \cdot \frac{1}{t \cdot R_a} \quad (2)$$

The installed laminar flow system may be influenced by the aerodynamic performance of any particular lamp. Therefore VDI 2167 [13] and DIN 1946-4 [14] require that the operating lamp is installed and in use when performing assessment measurements of the operating room ventilation system. Despite this inclusion, the use of an index is still useful for a hospital when selecting an operating lamp, or for designers when designing a new operating lamp.

Given the limited information on the validity of the LFI-index for the assessment of surgical lighting, in this research the hypothesis was tested whether the infection risk indeed is proportional to the projected surface area A [m^2] of the lamp, as suggested by the LFI. This was tested for three different lamp shapes in an isothermal environment. Following any definition of the LFI, a lamp without heat production would result in a laminar flow index of zero, which means that theoretically the lamp does not disturb the flow at all. Therefore, the risk will be compared directly to the projected surface area of each of the lamps. This results in a relationship between the size of the lamp shapes and whether a shape factor needs to be taken into account. The hypothesis was tested through an experimental and numerical study.

2. Method

To verify the validity of the LFI-index, the performance of the operating lamps has been evaluated using an alternative method. For this a modified version of the measurement method as described by VDI 2167 [13] has been applied. The influence of different surgical light shapes on the upward transport of particles is investigated, both experimentally and with the use of computer simulations. Variations in size and shape of the operating lamp have been made. The upward transport of particles was investigated for a test room with a laminar downflow plenum. Different lamp shapes were placed underneath the plenum. A fixed smoke source was placed on the floor, and the particle concentration underneath the lamp was examined.

According to Lidwell [2], in an operating room, the infection risk is proportional to the square root of the number of infected particles in the wound. As the emittance of particles in the experiments is significantly larger than in actual operating rooms, the relative infection risk (RR) increase is applied as performance indicator.

$$RR = \sqrt{\frac{C}{C_{ref}}} \tag{3}$$

Where C is the particle concentration measured 0.20m centrally below the lamp and C_{ref} is a reference concentration, which is defined as the concentration for a fully mixed situation. The definition of RR deviates from the VDI 2167 [13] that adopts a logarithmic scale of particle concentrations to express the cleanness of the wound area, stating ease of interpretation and not a relationship between Colony forming units (CFU) and infection incidence as the reason to do so. By using the Relative risk scale the lamp shape and the increase in infection risk is coupled directly.

The experimental results have been used to validate CFD calculations. The validated CFD-model has been applied to perform a sensitivity analysis on the size of the three different investigated shapes. A detailed description of the investigated geometry and conditions is given below.

2.1 Configuration

The measurements have been performed in a glass chamber with a stainless steel floor of 2×2×2m in which a downflow plenum has been built (see Figure 1). For the plenum, a so-called false ceiling is installed in the chamber that reduced the height of the ceiling to 1.65 m. The dimensions of the plenum are 0.98×0.98m and it is placed in the center of the false ceiling. The plenum consists of a thin fabric which provides a laminar downflow into the test room. The air velocity under the plenum was maintained at 0.3m/s. The air exhaust is located on the bottom of one wall, over the full width of that wall and with a height of 0.20m.

The supply air for the chamber is extracted from a large hall which is located alongside the room in which the test chamber is situated. The exhaust air is removed to the outdoor environment in order to prevent recirculation of particles. The air supply to the chamber passes a box with screen sections to minimize horizontal and vertical directed turbulence of the airflow that is delivered into the false ceiling.

Three different lamp shapes have been investigated: a classic closed shape; a semi-open shape with gaps in between the individual lamps, typically applied together with LED lights; an open shape with a configuration that comprises of 6 individual spots that are connected to a central hub. Photographs of the investigated shapes are shown in Figure 2. The projected surface areas of the individual shapes are given in Figure 2 as well. The lamp shapes were positioned centrally under the downflow plenum where the bottom of the lamp was 1.2m from the floor. The lamp shapes were suspended from the ceiling by means of thin iron wires.

The chamber represents the space between the plenum and the operating table on a real scale.

2.2 Measurements

Velocity and turbulence boundary conditions of the air flow at the supply plenum have been measured at a grid of 25 positions over the plenum. At each position measurements have been at 1Hz over a period of at least 300 seconds using a HT428 hot sphere anemometer with an accuracy of (0.02 m/s +1%). From these measurements an average supply velocity of 0.31m/s was determined, with a standard deviation of 0.01m/s and maximum deviation from this average of 11%. The air change rate for the room was calculated at 162 h^{-1}. The reason for the high air change rate is that the inlet velocity was chosen to be the same as in a real operating room. The lamp shapes were of a real size and the distance between the lamp and the floor was comparable to the distance between the operating table and a lamp in a real situation. As the measurement room was significantly smaller, the air change rate was larger than in a real operating room. The flow field directly around the lamp however can be assumed representative for a real situation.

Maximum turbulence intensity was measured at 7% at one position near the edge of the plenum. Average turbulence intensity was determined at 2.25%. Based on these results the airflow directly underneath the plenum was considered uniform and laminar. During the measurements of these boundary conditions no operating lamp was present. The supply flow rate was measured continuously during the experiments. To verify the isothermal situation, the supply temperature and the temperature of a representative wall inside the room were measured continuously as well.

Velocity and turbulence measurements have been performed in order to characterize the wake underneath the lamp. Measurements have been made on two cross sections perpendicular to the flow at 0.80 m from the floor, with 0.10 m intervals (see Figure 1). These measurements have been performed for the three different lamp shapes positioned in the test chamber and for the empty situation in which there is no lamp model in the chamber. Each measurement has been performed for at least 5 minutes, with a frequency of 1 Hz applying an omni-directional hot sphere anemometer. Measurements were taken sequentially using a single hot sphere anemometer.

For the particle measurements a constant smoke source (Palas AGF 2.0 IP) has been used. This smoke source was located centrally in the test chamber at 0.25m from the floor. Care was taken that the release of particles did not disturb the local flow field. The smoke inlet tube was connected to the bottom of a funnel. The top of the funnel was covered by a piece of course netting. In the middle of this netting a circular dot of duct tape was placed. This configuration takes the impulse out of the flow without filtering particles. The smoke concentration has been determined at 0.20 m (centrally) below the lamp, as well as directly underneath the plenum to determine the particle concentration at the supply. The reference concentration has been measured in a separate experiment where a large fan was introduced in the room to create a fully mixed situation. The particle concentration then was measured at the exhaust.

Smoke visualisations have been performed by positioning a projector outside the glass chamber that projected a sheet of light into the room. A dull black cloth was placed on the back side in the room, in order to improve contrast. Two different types of visualisations have been made for each investigated lamp shape. In both cases the flow field was filmed over time. For the first type of visualisation the chamber first was filled with smoke after which the smoke generator was turned off and the ventilation system turned on. The smoke removal from the chamber then was monitored. In the second type of visualisation the smoke source and the ventilation system were turned on simultaneously. This situation resembles the situation for which the actual particle measurements have been performed. By averaging the individual images in the film, the extent of the clean area has been determined.

2.3 Simulations

The visualisations indicated clearly that the flow pattern in the room is both three dimensional and transient. Therefore, 3D and transient CFD-simulations have been performed (Fluent 6.3.26[19]). The flow visualisations also showed that the flow underneath some of the lamp shapes is complex. In those cases a Reynolds-Averaging Navier-Stokes approach to solve the flow might not give sufficiently accurate results. Furthermore, it was identified that individual eddies play a mayor role in the upward transport of particles. Based on these considerations Large Eddy Simulation (LES) has been applied for solving the flow field.

Validation of the model follows the steps as defined by Chen and Srebric [20]. This is divided in two separate parts. First, velocity and turbulence measurements have been used to validate the simulated flow pattern. Then, the predicted particle concentrations are compared to the experiments.

Transport of particles in a flow field can be approximated by assuming that particles behave as a gas, indicated as Eulerian approximation. For this a concentration marker equation can be applied. With this approach particle concentrations can be derived directly. As an alternative, trajectories of individual particles can be calculated. This approach is indicated as the Lagrangian approach. The Eulerian approximation does not include the inertial effects of the individual particle and neglects the influence of gravity. The Lagrangian method does not simplify the inertial effects and the gravity force, but is more computationally expensive, because of the large number of particles that need to be tracked to arrive at a particle concentration distribution. A detailed discussion on the particle modelling approach is given in [21].

In this study both the Lagrangian and the Eulerian approach have been applied to assess their sensitivity towards the grid. In all cases it is assumed that the particles do not influence the flow field. For the Eulerian approach a marker equation was introduced. The concentration released at the particle source inlet surface was 1, and at the supply it was 0. The wall boundary conditions were for particles to bounce. The simulated particle concentration at the measurement location was logged and averaged over time. For the Lagrangian approach 150,000 particles were released per second at the surface of the particle source. After each time step the number of particles in a spherical volume of 1 litre centrally positioned around the measurement position was evaluated and averaged over time. Both Lagrangian and Eulerian approaches gave similar results. In the final sensitivity analysis the Lagrangian approach was adopted.

Grid dependency has been investigated for the semi-open lamp shape with a projected area of $0.35m^2$. Grid dependency has been assessed for the Relative infection risk (RR) performance indicator. An unstructured grid was applied consisting of tetrahedral cells. This was developed with Gambit 2.4.6. For the discretisation the chamber has been separated in three different areas. A denser grid has been defined for the volume around the lamp shape and the volume around the particle source supply. Table 1 presents the characteristics of the denser and general grid and the total number of grid cells applied in the grid sensitivity study.

The time step of the simulation was reduced for the denser mesh (from 0.5s to 0.2s to 0.1s) to arrive at expected maximum cell Courant numbers between 3.75 and 0.46, in line with Kornhaas [22].

Figure 3 and 4 present the progressive Relative infection risk as a function of time for the different time steps (relating to the calculation of the particle trajectories) and grid sizes (see Table 1). For example, at 50 s the lines indicate the average relative risk for the first 50 s. After a sufficiently long simulation time, the average relative risk will not change. The results of the different simulations converge to within a relative risk of 0.5.

Therefore, for the final simulations, a simulation time of 225 s, a time step of 0.1s and a grid size of 400 k cells has been used.

In order to predict the dependency of the Relative infection risk to the project area and the lamp shape. Four simulations have been performed of each investigated lamp shape scaled to a different size. The Relative infection risk is calculated for each of these simulations according to the method described and applying Equation 3.

3. Results

Figure 5 presents an example result from the smoke visualisation measurements for the second type of visualization that has been performed. The development of the flow pattern is shown at several consecutive time steps for the closed lamp shape. The particle source is well visible near the floor. Although the smoke source is constant and continuous, the flow pattern carries individual clouds of smoke through the chamber.

Figure 6 summarizes the results of the flow visualizations for the empty chamber and the different lamp shapes according to the second type of visualization performed. Here the individual images, refer to Figure 5, have been averaged. The darker areas indicate the particle (smoke) clouds. In three out of the four cases investigated the smoke builds up in an eddy on the right side of the room. The flow pattern changes when the (larger) semi-open lamp shape is positioned in the room.

Figure 7 presents two examples of the simulated complex velocity vector field in the test chamber. Figure 8 summarizes the comparison between the measured and simulated velocity profiles in the test chamber (see Figure 1). Results are shown for the three investigated lamp shapes.

The velocity profiles show that the velocity underneath the lamp is lower where the lamp blocks the flow. In case of the open shape the downward flow from the plenum is hardly obstructed by the lamp shape. The velocity peaks therefore are not as sharp as for the other lamp shapes. Visualization showed that the slightly higher average velocity in the middle of the semi-open shape is in the upward direction.

Based on these velocity results the models are considered to match the experimental conditions sufficiently well. Only for the semi-open lamp shape (Figure 8; perpendicular to exhaust) measurements show that most of the air flows directly to the exhaust, while in the simulation a considerable amount of air also flows downward on the far side of the lamp.

Based on the simulated velocity field the relative infection risk (RR) is determined. Figure 9 summarizes the measured and simulated results and presents the relative infection risk as function of the project area for the different investigated lamp shapes. As the projected area of the open lamp shape is significantly smaller than for the other two shapes the variation in projected area is less large.

4. Discussion

The results show that the experimental setup as applied was able to make a clear distinction between the different lamp shapes. The upward transport mechanism in the wake of the lamp shape varies between the different shapes and sizes. This is reflected in the combined measured and simulated results.

The test setup applied, however, differs in a number of aspects from a real operating room. Most notably, the test chamber is much smaller than a typical operating room. The exhaust opening was positioned at only one side of the chamber, which causes an eddy to appear on this side of the room. In an operating room, typically exhaust openings are distributed over the perimeter of the room. The measurements and simulations have been performed under isothermal conditions. As a result, the buoyancy effect of the lamps on the flow field has not been taken into account. All lamps were placed horizontally and centrally under the plenum, which is a worst case scenario. Placing the lamps under an angle can give different results. The method however can be extended to take these aspects into account.

Relative good agreement between measurements and simulations were found for two of the investigated lamp shapes (closed and open). For the semi-open lamp shape the airflow pattern in the room differed considerably. Though the simulation was able to predict this change in the flow pattern to some extend, the resulting particle concentration and relative infection risk was underpredicted (see Figure 9). Therefore the simulations are not proven to be accurate enough to make a distinction between the different lamp shapes. The general trend nevertheless is clear. Lamps with a projected area up to 0.1 m^2 do not interfere with the laminar downflow system in this configuration. With larger lamps the linear relationship between the surface area of the lamp and the infection risk is appropriate in the examined domain of projected areas.

This behaviour is expected to be applicable for more realistic situations as well, although the exact relationship with the relative infection risk will differ. This also accounts for different positions of the lamp and the design of the laminar downflow system.

The original definitions of the Laminar flow index (Formula 1 and 2) assume no disturbance when no heat is produced by the lamp. The results presented in this paper clearly show that, even though the situation is completely isothermal, in some cases the airflow can be disturbed considerably by the lamp shape. Therefore, the laminar flow index cannot be considered valid for lamps that produce a negligible amount of heat.

5. Conclusions

The projected area of a lamp is a good indicator for the infection risk. The relationship between the projected area and the infection risk is close enough that it is a useful indicator in practice.

Lamps up to a certain size will not disturb the flow at all, and therefore the airborne infection risk in these experiments is considered zero. In that case the lamp is small enough and allows dissolving of the turbulent wake downstream of the lamp before it reaches the smoke source. This effect is not included in the original formula for the LFI.

The shape of the lamp seems to have some influence on the relative infection risk, but the simulation results were not accurate enough to differentiate between the shapes.

While the lamps in these experiments did not produce any heat, their size did influence the particle distribution in the room. This is not predicted by either Laminar flow index formula and therefore these formulas are not suited for lamps with a low heat output.

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References

[1] Dankert, J., Zijlstra, J.B., Lubberding, H (1979). "A garment for use in the operating theatre: the effect upon bacterial shedding." The Journal of Hygiene 82(1): 7-14.

[2] Lidwell, O. M., Lowbury, E.J.L., Whyte, W., Blowers, R., Stanley, S.J., Lowe, D (1983). "Airborne contamination of wounds in joint replacement operations: the relationship to sepsis rates." Journal of hospital Infection 4: 111-131.

[3] Ham, P. J. (2004). Handboek ziekenhuisventilatie. TNO Prevention and Health. Leiden, The Netherlands.

[4] Memarzadeh, F., and A. Manning, 2002, Comparison of operating room ventilation systems in the protection of the surgical site, ASHRAE Transactions 108(2)

[5] CBZ (2004). Bouwmaatstaven voor nieuwbouw Operatieafdeling. College Bouw Zorghuisvesting. Utrecht, the Netherlands, ISBN 90-8517-008-7.

[6] NHS Estates (2004). Ventilation in Healthcare premises, design considerations. National Health Service. London, United Kingdom.

[7] Zoon, W. A. C., Schotel, D (2004). Computer simulations of laminar air flow systems in operating theatres. Proceedings: Technik im Krankenhaus. Hannover, Germany. pp. 287 -296

[8] Loomans, M., van Houdt, W, Lemaire, AD, Hensen, JLM (2008). "Performance Assessment of an Operating Theatre Design Using CFD Simulation and Tracer Gas Measurements.". Indoor Built Environ 2008;17;4:299-312

[9] Rui Z, et al. Study on biological contaminant control strategies under different ventilation models in hospital operating room. Building and Environment (2007), doi:10.1016/j.buildenv.2007.01.018

[10] Brohus, H., Balling, K.D. and Jeppesen, D. (2006) Influence of movements on contaminant transport in an operating room, Indoor Air, 16, 356–372

[11] Melhado, M., Hensen, JLM, Loomans, MGLC, Forejt, L (2006). Review of operating room ventilation standards. Proc. 17th Int. Air-conditioning and Ventilation Conference, Prague, Czech Republic.

[12] SWKI (1999). Richtlinie 99-3 Heizungs- Lüftungs- und Klimaanlagen in Spitalbauten. Schönbühl, SWKI.

[13] VDI (2007). Technische Gebäudeausrüstung von krankenhäusern Heizungs- und Raumlufttechnik (VDI-Lüftungsregel). VDI 2167. Verein Deutsche Ingenieure. Düsseldorf, Germany.

[14] DIN (2008). DIN 1946 Raumlufttechnik - Teil 4: Raumlufttechnische Anlagen in Gebäuden und Räumen des Gesundheitswesens. Deutsches Institut für Normung e.V. Berlin, Germany

[15] Chow, T.T., Zhang Lin, Wei Bai, 2006, The integrated effect of medical lamp position and diffuser discharge velocity on ultra-clean ventilation performance in an operating theatre, Indoor Built Environ 2006;15;4:315-331

[16] Leenemann, J. (1986). Licht en lucht in de operatiekamer. Techniek in de Gezondheidszorg. 2: 26-29.

[17] Walenkamp, G. H. I. M. (2005). Beheersplan Luchtbehandeling voor de Operatieafdeling. Werkgroep Infectiepreventie. Maastricht, the Netherlands.

[18] Oostlander, K. (1991). Operating room lamps. Medical Focus: 46-49.

[19] Fluent 6.3 user's guide, Fluent Inc, Lebanon, US (2006)

[20] Chen, Q., Srebric, J (2001). How to Verify, Validate, and report Indoor Environment Modeling CFD Analyses, Ashrae RP-1133.

[21] Zhang, Z., Chen, Q (2007). "Comparison of the Eulerian and Lagrangian methods for predicting particle transport in enclosed spaces." Atmospheric Environment 41: 5236-5248.

[22] Kornhaas, M., Sternel, DC, Schäfer, M (2008). Influence of time step size and convergence criteria on large eddy simulations with implicit time discretisation. In: Quality and reliability of large-eddy simulations, Meyers, Johan; Geurts, Bernard J.; Sagaut, Pierre, ISBN: 978-1-4020-8577-2 Springer Netherlands. 12: pp.119-130.

Figure 1. Sketch of the test chamber in which the lamp shapes were tested. Velocity profiles have been measured at the two lines underneath the lamp.

Figure 2. Photographs of the experimentally investigated lamp shapes.

Figure 3. Relative infection risk as a function of time for different time steps for the calculation of the particle trajectories applying the Lagrangian approach. The 400k cells case has been used in the final calculations. The semi-open lamp shape has been used.

Figure 4. Relative infection risk as a function of time for the different investigated grids at 0.1s time steps. The semi-open lamp shape has been used.

Figure 5. Visualized smoke pattern in the test chamber for the closed lamp shape, for a constant particle source. Images are shown for an interval of 3.3 seconds.

Figure 6. Visualized average smoke concentration in the test chamber, for a constant particle source, for the empty chamber and the different investigated lamp shapes. Averaging is performed over at least 50 images.

Figure 7. Examples of the simulated velocity vector field for the test chamber with the closed lamp shape (left) and the semi open lamp shape (right) colored by velocity [m/s].

Figure 8. Comparison of measured and simulated velocity profiles at 0.8m height in the test chamber (see Figure 1). Velocities shown are average values of velocity magnitude.

Figure 9. Simulated and measured relative infection risk at function of the projected area for the different investigated lamp shapes.

Table 1. Grid characteristics as applied for the grid dependency study.

Case	number of cells	grid size details [mm]	grid size general area [mm]
200k cells	253829	32.5	65
400k cells	385603	30	50
800k cells	852925	25	40