The Research of Reflective Cones and Mirrors for LED Surgical Luminaire Medical Modules

Kuan-Ling Yu*, Shih-Chang Shei, Man-Ching Huang and I-Ching Tsai
Department of Electrical Engineering
National University of Tainan, Tainan, 70005, Taiwan
*E-MAIL : S10582017@gm2.nutn.edu.tw

Abstract

Surgical lamps are extremely important equipment for surgical lamps. Traditional surgical lamps use halogen lamps as the light source. The illumination method is full-circumferential illumination. The market is mostly reflective. However, the halogen source is not only the source of the halogen. With high heat energy, it may cause secondary injury to the wound of the patient, and the energy consumption is up to 150W. It is very inconsistent with the concept of environmental protection. The shortcomings mentioned above will be the reason why the traditional surgical lamp with halogen lamp must be transformed.

Compared with the general commercially available surgical lamps, the surgical light module designed in this study aims to replace the halogen light source of the traditional lamps, improve the high energy consumption caused by the halogen lamps, and the heat radiation in the light, and Breaking through the design of LED surgical lamps in the past, reducing the use of a large number of LED light sources, improving the phenomenon of uneven color temperature and ghosting.

At present, the reflection that has not been adopted on the market is an LED light source surgical light. This is because, unlike the traditional structure, there will be a cost problem in the replacement. If it succeeds, the light will be directly replaced without changing the outer layer. By assembling the components, you can save a lot of cost. The motivation of this thesis is that while pursuing compliance with regulations, it can also pursue the maximum benefits of cost (lighting replacement) and environmental friendliness (LED).

Keywords: Reflective cone, LED Surgical Luminaire Medical Modules, Collimating cup, Reflection Angle, Reflection lens.

----

* Corresponding author:S10582017@gm2.nutn.edu.tw
DOI：10.3966/222344892020101002001

I. INTRODUCTION

Since the invention of the electric light, it has greatly changed the way people live. But with advances in technology, people began to demand for quality lighting, in addition to the durability of the lamp itself, or not for a friendly environment, as well as different conditions require some light source requirements, for which organized Beginning to establish regulations to ensure the quality of lighting when people use the luminaire.

The LED is a light-emitting element in which a semiconductor is used as a light-emitting material, and photons are emitted by recombination of carriers in the semiconductor, so that there is no problem of heat radiation. In addition, the wavelength of the light can be determined by the energy gap of the material, and the wavelength range covers the ultraviolet to infrared light band, and the color is diversified. Compared with incandescent tungsten bulbs and fluorescent lamps, white LEDs have many advantages: environmental protection, good vibration resistance, small size, flat package, fast response, and long life of more than 100,000 hours. The biggest advantage is that LED power consumption is extremely high. Low, the energy consumed is only 10% of the traditional light source.

According to statistics, more than 50 million surgeries are performed each year in the world. Surgical luminaires are the most important equipment in surgical operating room. The publication [1] revised by the International Electro-Technical Commission (IEC) in 2009 is the most authoritative standard for surgical luminaires. As a member of IEC, the Chinese standard of surgical luminaires [2] is basically the same as that of IEC. The design of surgical luminaires covers a wide range of areas, including optics, machinery, electricity, control, appearance, safety and so on. This paper will not give a comprehensive introduction to the design of surgical luminaires, but focus specifically on some of the most important optical problems that must be considered in the overall design of variable spot surgical lamps. According to the IEC standard, the following parameters are used to describe the light field of a surgical lamp: Light field center LFC: usually the point of maximum illumination in the light field. Center illuminance Ec: the illuminance at LFC Light field diameter: diameter of a circle around LFC where the illuminate reaches 10% of Ec. See Figure 1 The distribution of light field parameter D50: diameter of a circle around LFC, the illumination on the circle is 50% of EC. Depth of illumination: the depth of the region below the emitting surface, of which the illumination is at least 60% of that of EC. As article [3] described, IEC standard is the most important document for the design of surgical lamp.

However, the requirement of IEC standard for the distribution of surgical lamp light field is very simple. That is the minimum diameter D50 needs to be at least 50% of D10. This requirement can be expressed as (1) and (2):

$$c = D_{50}/D_{10} \qquad (1)$$

$$c \geq 0.5 \qquad (2)$$

In fact, (1) and can be visually understood as requiring a certain degree of “fullness”. The larger the c is, the “fuller” the shape is, and the more uniform the illumination will be. Thus we will be referring to the shape parameter "c" as “fullness” in this paper.

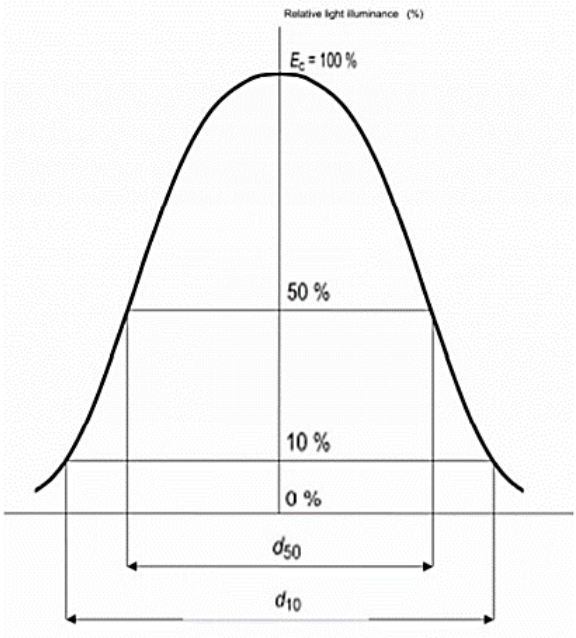


Figure 1. Light distribution of surgical field, (quoted from [1] p22).

II. Modified Gaussian Function to Simulate the Illumination Distribution of Surgical Lamp

The Gaussian function [4] has important applications in natural sciences, Social Sciences,mathematics and engineering. In the field of optics, the intensity distribution of a laser beam with parallel beam shape has proven to be a Gaussian function [5]. Among the issues we are discussing, the beam angle of surgical lamp is very small, it has a near parallel light beam shape, and so the intensity distribution could and should also be described using a one-dimensional Gaussian function [6]

$$y = \exp(-\frac{1}{\sqrt{2}}\left(\frac{r}{w}\right)^2) \qquad (3)$$

Here r is the distance from the origin of coordinate, w is the half width of the function peak. In order to describe the illumination distribution of surgical lamp better, the function (3) should be modified. To do this, add parameters d and a(c), then change (3) to (4):

$$y = \exp(-d\left(\frac{|r|}{w}\right)^{a(c)}) \qquad (4)$$

The fixed exponent 2 in formula (3) was changed to the function a (c), then the relationship between illumination y and shape parameter c can be described. And d is a parameter describing the width of the spot. You can find an interesting but important and useful property of (4) that when w is fixed, the curves of different a(c) will intersect at the point of r=w and the height of the intersection is y=e-d. Then d can be used as a parameter to control the height of intersection points. This property can be seen more clearly in Figure 2. This is why we add parameter d into (4). On the other hand, as can be seen from Figure 1, D_{10} is the size of the spot, so make the intersection point is 0.1 high:

$$0.1 = exp(-d)$$

Solving the equation, we get

$$d = 2.30259 \tag{5}$$

So function can be turn into

$$y = \exp(-2.30259\left(\frac{|r|}{w}\right)^{a(c)})$$

Then the following equation is solved by the definition of D_{10}

$$0.1 = \exp(-2.30259\left(\frac{|r|}{D_{10}/2}\right)^{a(c)})$$

Get (6):

$$D_{10} = \frac{2r}{exp(-2.58592*10^{(-12)}/a(c))} \tag{6}$$

Similarly, D_{50} can be obtained as (7):

$$D_{50} = \frac{2r}{\exp(-1.20054/a(c))} \tag{7}$$

From simultaneous equation (1), (6) and (7), a(c) can be get as

$$a(c) = -\frac{\ln(\ln(2)/\ln(10))}{\ln(c)} = \frac{1.200545}{\ln(c)} \tag{8}$$

The expression of illumination distribution can be obtained as follows

$$f_0(r,b,c) = \exp\left(-2.30259\left(\frac{|r|}{w}\right)^{\frac{1.200545}{\ln(c)}}\right) \tag{9}$$

With this multivariate function (9), we can mathematically describe the illumination distribution of surgical lamp with the spot radius w and the saturation parameter c conveniently. Graphics of the functions can be easily drawn by using mathematical software Maple or Mathlab. Figure 2 shows the curves of illumination function f_0(r, b, c) varying from c=0.5 to 0.9 with a fixed single spot radius w=100mm. The curves intersect at r=100. This kind of figure can easily describe various illumination distributions when the spot is D_{10}, and it helps us complete our analysis in this paper.

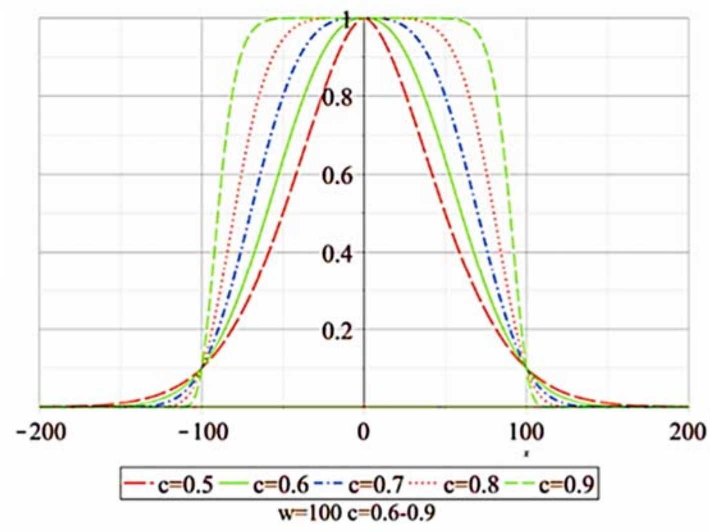


Figure 2. Illumination distribution function of single light spot.

The illumination area is composed of seven light beams, which are described by seven two-dimensional Gaussian functions [7]. The seven beams are shown in Figure 3

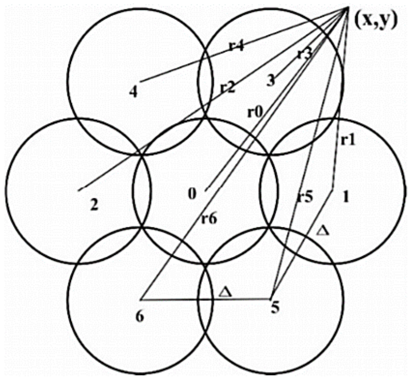


Figure 3. Schematic diagram of 7 light spots

The coordinate origin of x and y is at the center of the beam number 0, and the other six beams are symmetrically distributed. All the distance between two adjacent centers are Δ. The radii of these seven circles can be expressed by (10).

$$\begin{cases} r_0 = \sqrt{x^2 + y^2} \\ r_1 = \sqrt{(x-\Delta)^2 + y^2} \\ r_2 = \sqrt{(x+\Delta)^2 + y^2} \\ r_3 = \sqrt{(x-\frac{1}{2}\Delta)^2 + (y-\frac{\sqrt{3}}{2}\Delta)^2} \\ r_4 = \sqrt{(x+\frac{1}{2}\Delta)^2 + (y-\frac{\sqrt{3}}{2}\Delta)^2} \\ r_5 = \sqrt{(x-\frac{1}{2}\Delta)^2 + (y+\frac{\sqrt{3}}{2}\Delta)^2} \\ r_6 = \sqrt{(x+\frac{1}{2}\Delta)^2 + (y+\frac{\sqrt{3}}{2}\Delta)^2} \end{cases} \tag{10}$$

Expression (9) is the illumination distribution function of beam number 0. The all seven functions with five independent variables then can be written as (11) (i=0…6).

$$fi(x,y,w,c,\Delta)=\exp\left(-2.30259\left(\frac{r_i(x,y,\Delta)}{w}\right)^{\frac{1.200545}{\ln(c)}}\right) \qquad (11)$$

According to the superposition principle of incoherent light, the total spot distribution with five independent variables is simply the sum of seven Gaussian functions:

$$F(x,y,w,c,\Delta)=f_0+f_1+f_2+f_3+f_4+f_5+f_6 \qquad (12)$$

On the special cross section passing through the center of the spot (y=0), the illumination distribution of three spots (13) can be simplified as a function of four independent variables

$$\begin{cases} fx_0(x,w,c,\Delta)=\exp\left(-2.30259\left(\frac{|x|}{w}\right)^{\frac{1.200545}{\ln(c)}}\right) \\ fx_1(x,w,c,\Delta)=\exp\left(-2.30259\left(\frac{|x-\Delta|}{w}\right)^{\frac{1.200545}{\ln(c)}}\right) \\ fx_2(x,w,c,\Delta)=\exp\left(-2.30259\left(\frac{|x+\Delta|}{w}\right)^{\frac{1.200545}{\ln(c)}}\right) \end{cases} \qquad (13)$$

The total illumination distribution is

$$Fx(x,w,c,\Delta)=fx_0+fx_1+fx_2 \qquad (14)$$

In many cases, two-dimensional global distribution (12) can be described by one-dimensional illumination distribution (14).

III. INSTITUTIONAL DESIGH AND ANALYSIS

We refer to the manufacturer's model and improve it, through the control of various variables, and the results of the simulation to explore the relationship between components and light sources.

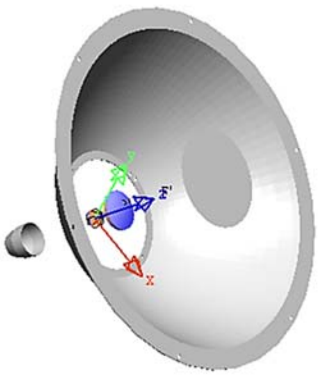


Fig 4. Explosion map of the model

As shown in the above figure, the model contains the collimating cup and the lens of the path used to focus the light source. After the light passes, it will pass through the reflection cone, and then touch the peripheral light to reflect the second time and finally reach the plane. We will separately discuss the effect of the reflection cone and the value of the quasi-cup on the light source.

Conforms to international regulations IEC 60601-2-41:2000.

Project Name	Scope of the specification
Center maximum illumination (Ec)	40,000Lux≤Ec≤160,000Lux
Spot requirement (D50、D10)	D50≥0.5*D10
Color rendering (Ra)	85≤Ra≤100
Color temperature (Te)	3,000°K≤Te≤6,700°K

Table 1. international regulations IEC 60601-2-41:2000.

3.1 Reflective cone design and analysis

When discussing the collimating cup, the reflection cone is split into the presence or absence of the second reflection angle for simulation with *Light Tools*, as shown in the following figure 4.

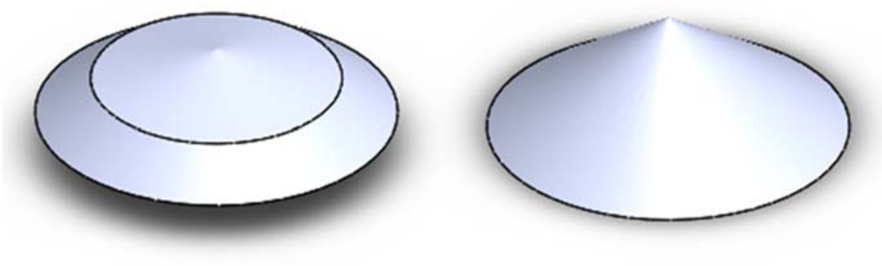


Fig 5. Simulate the reflection cone with *SOLIDWORKS*

3.1.1 Discussion of reflection cones at various angles

We first preset the use of a circular collimating cup, and first placed the reflecting cone at a distance of 71.9 mm from the collimating cup, regardless of the effect of the lens. The bottom of the reflection cone is taken at 90~120cm, and the first reflection angle is preset to 35 and 40 degrees.

	90cm	100cm	105cm
35 degrees	center: 64798 Maximum: 76534 Ratio: 0.319	center: 64798 Maximum: 76534 Ratio: 0.319	center: 52326 Maximum: 55433 Ratio: 0.29
40 degrees	-	-	-

	110cm	115cm	120cm
35 degrees	center: 28122 Maximum: 32746 Ratio: 0.38	-	-
40 degrees	-	-	-

Table 2. Reflective cone simulation results for each length and angle

As can be seen from the above table, the simulation results are not satisfactory, but it can be seen that if the bottom width is smaller, the reflection cone simulates a better value. So, we will do further simulations, taking 80cm and 85cm as the bottom length.

	80cm	**85cm**
35 degrees	center: 69779.16602 Maximum: 79200.41788 Ratio: 0.6	center: 69517.61838 Maximum: 77477.65174 Ratio: 0.5624
40 degrees	center: 57843.41394 Maximum: 61587.03103 Ratio: 0.311	center: 41184.07064 Maximum: 46341.66709 Ratio: 0.29

Table 3. simulation results of 80cm, 85cm

It can be found from the above table that at 80cm and 85cm, although some of the reflection cones still do not comply with the regulations, there has been a significant improvement. Next, let's explore whether the second reflection angle will affect the simulation results.

3.1.2 Discussion on the Second Reflection Angle

As shown in the figure below, we first remove the thickness of the reflection cone from the left and right sides by 12cm, and then remove the second reflection angle.

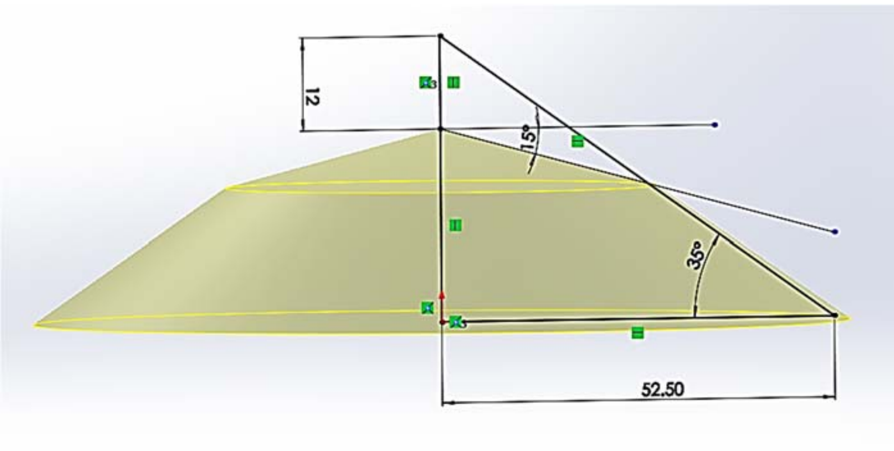


Fig 6. A reflective cone that adds a second reflection angle

This time, we will still take 90~120 cm as the bottom length of the reflection cone. At the first reflection angle, we will take 35, 40, and 45 degrees, and the second reflection angle will be 15, 20, and 25 degrees as the change elements.

The first reflection angle	The second reflection angle	90cm	100cm	105cm
35°	15°	0.331	0.4375	0.5
	20°	0.365	0.46824908	0.49107
	25°	-	-	0.584
40°	15°	-	-	-
	20°	0.32	-	-
	25°	0.3	-	-
45°	-	-	-	

Table 4. 90~105 cm spot ratio simulation results with *Light Tools*

By comparing the illumination simulation with the spot ratio, the smaller the angle and the smaller the bottom width, the better the results are simulated.

Finally, we can make a conclusion here: since the measured value is in compliance with the regulations when the first reflection angle of 90cm is 40 degrees and the first reflection angle of 85cm is 40 degrees, it can be seen that the length of the bottom is shortened to a certain extent. After that, the size of the length no longer has a significant effect on the simulated results.

3.2 Discussion on Collimating Cup of LED Surgical Light

3.2.1 Collimating cup analysis with smooth or folded cup wall

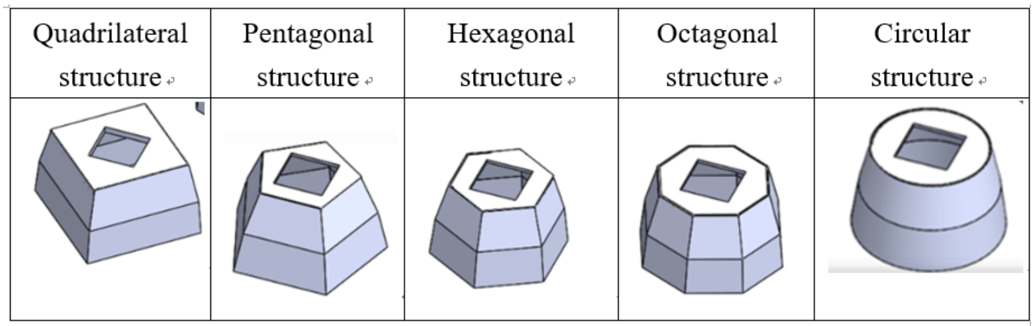


Fig 7. Transition collimating cup

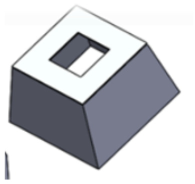
Quadrilateral structure	Pentagonal structure	Hexagonal structure	Octagonal structure	Circular structure
				

Fig 8. Smooth collimating cup

As shown in Fig 7 and Fig 8, for the collimating cups with different shapes at the bottom, the following results are obtained by using the Light tool program, as shown in Table 5, Table 6 and Table 7.

	Smooth collimating cup	**Transition collimating cup**
Quadrilateral	37282	46936
pentagon	38474	39534
Hexagon	42894	56121
Seven-pointed shape	45258	-
Octagon	44957	56879
circle	68721	83109

Table 5. Center illumination simulation result

	Smooth collimating cup	**Transition collimating cup**
Quadrilateral	42242	51789
pentagon	44015	47773
Hexagon	42894	67149
Seven-pointed shape	47304	-
Octagon	54679	63797
circle	78090	84789

Table 6. Maximum illumination simulation result

	Smooth collimating cup	**Transition collimating cup**
Quadrilateral	0.50	0.457
pentagon	0.54	0.532
Hexagon	0.499	0.557
Seven-pointed shape	0.51	-
Octagon	0.57	0.553
circle	0.545	0.5046

Table 7. Spot ratio simulation result

Based on the above simulation results, the following conclusions can be drawn:

1. As the number of polygon edges at the bottom increases, both the center illuminance and the maximum illuminance increase.
2. The distribution of the even number of apertures is more uniform.

3. In terms of the comparison of the illuminance, the turning collimation cup has better performance.
4. The spot ratio of the turning collimating cup is slightly lower than that of the smooth collimating cup.
5. In addition to the quadrilateral turning collimation cup does not meet the legal standard of the spot ratio, the rest are in accordance with the statutory specifications of the central illumination and the spot ratio.
6. Combining the above 5 points, the circular turning collimating cup is the best sample.

3.2.2 Explore the size of the opening cup and the length of the cup

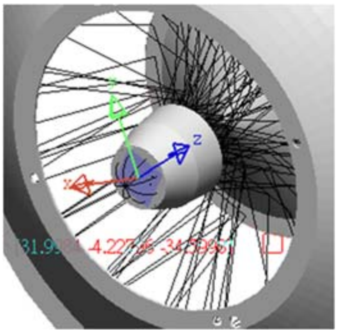
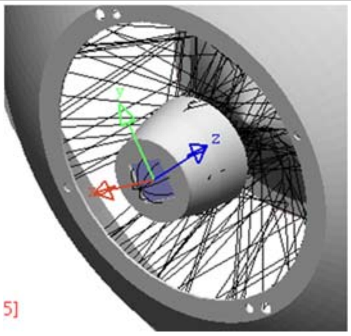
		
Round turning collimating cup	**New (left)**	**Old (right)**
Bottom circle radius	10.5mm	15mm
Center illumination	98391	83109
Maximum illumination	109862	84789
Spot ratio	0.539	0.504

Table 8. Simulation results with different opening sizes

Round turning collimating cup	**Short**	**Long**
Bottom circle radius	24mm	30mm
Center illumination	109724	98018
Maximum illumination	126210	106049
Spot ratio	0.519	0.591

Table 9. Simulation results of different cup lengths

Based on Tables 8 and 9, the following conclusions can be found:

1. The illuminance and spot ratio of the collimating cup have a small opening radius, and the illuminance and the spot ratio are excellent.

2. The longer length of the collimating cup has a better spot ratio, but it is slightly inferior to the short collimating cup in terms of illuminance.
3. Combine the above two points, and in order to meet the requirements of the statutory regulations, a circular turning collimating cup with a bottom radius of 10.5 cm is finally adopted as the specification of the collimating cup of this study.

3.2.3 Discuss the effectiveness of the collimating cup into the lens

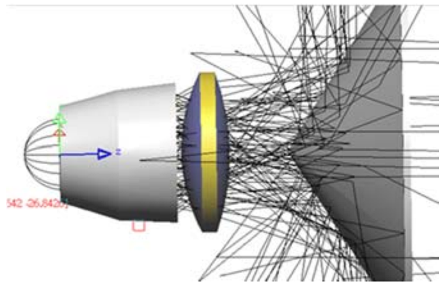
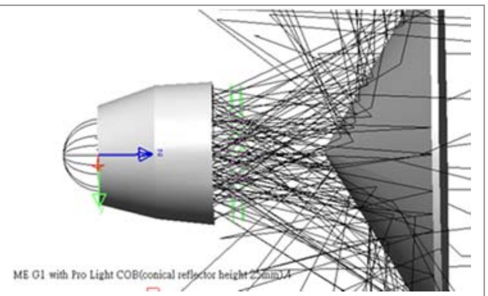
		
Whether to add a lens	**Add lens (left)**	**No lens added (right)**
Center illumination	109724	98391
Maximum illumination	126210	109862
Spot ratio	1.591	1.539

Table 10. Whether to add a lens simulation result after collimating the cup

According to Table 6, it can be known that adding a lens can make the light more concentrated. Although the spot ratio is slightly lower, it is the goal pursued by the Institute to meet the legal specifications. Therefore, it was decided to add the lens to the module.

3.2.4 Module Materialization

The core module development of LED surgical light in this study is divided into 7 parts, as shown in the exploded view of the core module structure of LED reflective surgical light, as shown in Figure 9, including: disc, LED base, collimating reflector cup, the lens collar upper cover, the lens collar lower cover, the spherical lens, and the first mirror are all drawn by the SolidWorks drawing software.

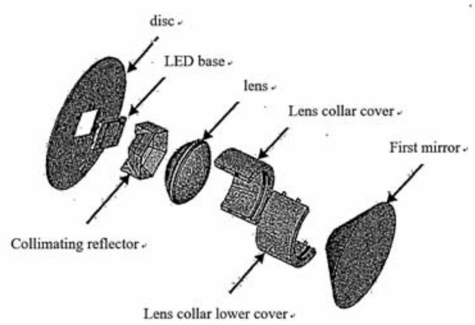


Fig 9. Reflective surgical lamp core module structure explosion diagram

IV. CONCLUSIONS

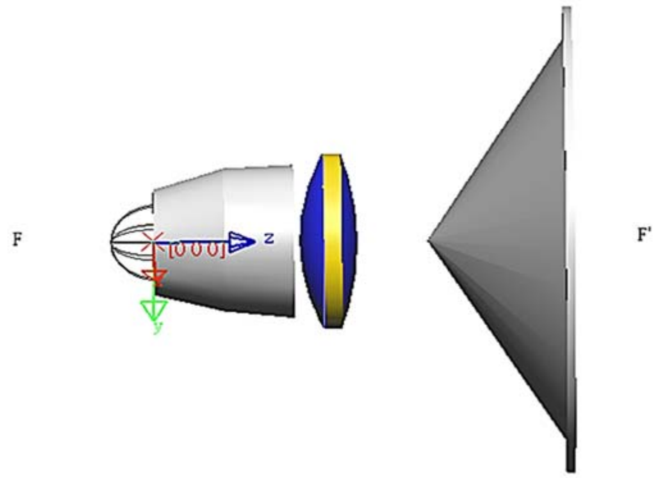


Fig 10. Simulate the finished product with Light Tools software

Center illumination: 109724

Maximum brightness: 126210

Spot ratio: 1.16

This study is based on the laws of geometric optics, designing secondary optics, which is the core component of this research, including: collimating reflector, spherical lens, first mirror and other components, and with COB LED light source, and finally the light source and core components are physically mounted on the second mirror of the DomeLux 6200 halogen source surgical luminaire and physically measured to verify compliance with the IEC 60601-2-41:2000 specification for surgical luminaires. Development. The main research results are as follows:

1. With a single output power of only 43W COB LED light source and core module components, the maximum illumination can approach 100,000 Lux, D10 and D50 spot ratio value of 1.1 or more, in line with surgical lamps IEC 60601- 2-41: 2000 specification.
2. Compared to traditional halogen light source surgical lamps, it is expected to reduce lamp consumption by more than 70%.
3. This study not only improves the shortcomings of traditional surgical lamps using halogen lamps, but also improves the current replacement of LED light sources, which is difficult to apply to reflective surgical lamps.
4. The core module components of this study can be directly installed on the second mirror of the DomeLux6200 traditional light source without replacing the entire set of surgical lamps, which will greatly reduce the replacement of the light source, and the cost which surgical lamps need to be redeveloped.

This study used a single COB LED light source to work with the core module and was mounted on a conventional halogen source reflective surgical luminaire. However, due to the old mirror of the traditional halogen source being too old, the ruthenium of the reflective layer was oxidized. Phenomenon, which causes the loss of light energy, and also due to multiple depressions during disassembly, resulting in spot diameter and slight error, but the error is within the allowable range and meets the spot ratio specified in the specification.

This study was based on the commercially available DomeLux 6200 halogen source surgical luminaires.

Therefore, the core module of this study design should be limited to the condition that the second mirror is in the shape of a circular array. In the future, according to the core module structure designed in this study, and with the geometrical optical law operation or the optical trajectory inverse calculation of the spot shape, it can be applied to the traditional light source second mirror with different shapes, different sizes and different angles. on. This core module design can not only be used as a publication of academic papers, but also replace the core light source of commercially available traditional halogen light source surgical lamps. The university saves domestic and foreign medical institutions, and needs to replace the entire set of surgical lamps and raise the LED. The application of light sources to luminaires reduces the dependence of domestic manufacturers on foreign technology to create opportunities for competition between Taiwan and other advanced countries.

V. REFERENCES

[1] IEC (International Electro-technical Commission) Standard 60601.2.41 2009 Particular requirements for basic safety and essential performance of surgical luminaires and luminaires for diagnosis Submission.

[2] National Pharmaceutical Industry Standards [S], YY0627- 2008.

[3] Knulst A J, Stassen L P S, Grimbergen C A, et al. “Standards and Performance Indicators for Surgical Luminaires” [J]. LEUKOS, 2009, 6 (1): 13.

[4] Hongwei Guo, "A simple algorithm for fitting a Gaussian function" [J], IEEE Sign. Proc. Mag. 28 (9): 134-137 (2011).

[5] Oren Aharon, “Laser beam profiling and measurement” [J], Novus Light Technologies Today, (2013).

[6] Nathan Hagen, Matthew Kupinski, and Eustace L. Dereniak, “Gaussian profile estimation in one dimension” [J], Appl. Opt. 46, 5374-5383 (2007).

[7] N. Hagen and E. L. Dereniak, “Gaussian profile estimation in two dimensions” [J], Appl. Opt. 47:6842–6851 (2008).