Quality Assessment of Virtual Prototypes of Surgical Luminaires using Near-field Ray-data

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Abstract—Surgical luminaires are an important tool for the surgeon, yet highlighting the wound of a patient is not trivial and surgical luminaires must meet stringent regulatory requirements. Optical requirements and performance indicators are described in the European Standard for surgical luminaires and they must be measured after construction. Surgeons and hospital managers often use these performance indicators to compare different surgical luminaires. The introduction of solid-state lighting and high-power light emitting diodes (LEDs) has initiated a new generation of surgical luminaires. When designing a virtual prototype of a surgical luminaire it would be beneficial to have a cost- and time-effective method to test luminaires for compliance with the European Standard. Unfortunately, far-field intensities do not allow an evaluation of these luminaires with respect to the standard and near-field ray-data must be used. To validate this near-field approach, we used angular- and spatially-resolved ray-data of a luminaire and modeled a virtual setup that corresponds to the setup used in the European Standard. This paper compares illuminances obtained from simulations and photometric measurements of various photometric tests. Good agreement was found: relative differences between simulations and measurements for the central illuminances deviate maximally 0.4 percent (+ 3.2 percent, -0.4 percent), while the maximum difference for the various scenarios amounts to 5.6 percent (± 2.2 percent). The technique can be applied to virtual prototypes of surgical luminaires.

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luminaires that are composed of optical components such as reflectors and lenses and use spatially- and angular-resolved luminance-data of individual LEDs. This permits us to check compliance with the European Standard before assembly. This method will allow for more economical and time-effective development of new luminaires that maintain the quality requirements.

Keywords—Standards, performance, surgical luminaire, LED, simulation, near-field goniophotometry.

1 INTRODUCTION

A surgical luminaire is an important tool available to the surgeon in order to discriminate and perceive anatomic detail, while minimizing shadows when the medical staff partially obstructs the light [Beck 1974, 1978, 1981; Dain 1998; Ersek 1972a, 1972b; Fisher 1978; Knulst 2009a, 2009b; Loonam 2003]. The design of a surgical luminaire is a complex task, as various optical requirements should be met. This task is further complicated by thermal and mechanical requirements that may interfere with the optical performance of a surgical luminaire.

The European Standard NEN-EN-IEC 60601–2-41 [IEC 2009] describes various requirements for basic safety and necessary performance of surgical luminaires. Both photometric and spectral measurements have to be performed to characterize the light intensity, beam width and color rendering index (CRI). The results of these tests have to be specified by the manufacturer. Detailed requirements to test the optical performance of a surgical luminaire under various conditions that mimic real surgery are also given. A deep wound is modeled by a black tube and the head of the surgeon and a surgical assistant is modeled by masks, positioned in different geometries that partially block the light beam.

Due to recent advances in light emitting diode (LED) technology, LED-based surgical luminaires are now commercially available, alongside traditional surgical lighting using tungsten halogen or high intensity discharge (HID) lamps. The spectra of LEDs contain mainly visible wavelengths. LED luminaires thus reduce heat problems due to the absence of infrared radiation in the light beam. Heat may cause discomfort to the surgeon while operating. In more extreme cases heat problems such as dehydration and burn wounds have been reported for traditional lighting when the IR filter was out of place. [Fisher 1978].

It would be beneficial to have a time- and cost-effective method to predict illuminances in the surgical site and to test if a virtual prototype of a surgical luminaire complies to [IEC 2009], before building the device. Traditionally, calculations of the illuminance on a task area are performed analytically, using the well-known far-field luminous intensity-distribution of the luminaire. Due to the narrow beam of the typical surgical luminaire, large measurement distances are required [Moerman 1981].

However, these far-field intensities cannot be used to test for compliance to [IEC 2009] because illuminances in the near-field region of the luminaire need to be known. [Stannard 1990, 1992] As a result, this method cannot be used to test virtual prototypes of surgical luminaires for compliance to the European Stan-
standard and time-consuming measurements have to be performed after prototypes have been built. A different approach is needed.

The last couple of decades, near-field goniophotometers have been developed in an attempt to understand the light distribution close to the light source. [Ngai 1992, 1993] Ray data and intensity distributions can be determined by rotating both a luminance camera and an illuminance meter around the light source. [IESNA 2005]

This paper shows that angular- and spatially-resolved ray-data of the luminaire can overcome the previously mentioned problems. The method will enable to test for compliance to the European Standard. The luminance data can be: a) measured for existing luminaires, using a near-field goniophotometer, or b) inserted in simulation software using ray data as individual rays or surface sources.

This paper is structured as follows. Section 2 Methods describes the luminaire under consideration, then it shows that analytical calculations based on far-field intensities are inadequate to obtain correct illuminances in the surgical site and finally it also explains how ray files were obtained by a near-field goniometer and used in simulation software to obtain illuminances. Section 3 Results will show that simulated illuminances based on ray data and a virtual model correspond well to experimental illuminances determined by a photometer for all photometric experiments outlined in [IEC 2009]. Consequently, it shows that performance indicators derived from the illuminance distribution, also correspond. These performance indicators are (remaining-) central illuminance, light-field size and depth of illumination. Section 4 Conclusions elaborates on the impact of this method for developing virtual prototypes in a time-efficient and economical way.

2 METHODS

2.1 SURGICAL LUMINAIRE UNDER CONSIDERATION

The surgical luminaire under consideration is a commercially-available surgical luminaire composed of 2 × 84 LEDs that are placed in a rotationally-symmetric shape. The correlated color temperature (CCT) can be adjusted by the surgeon (3600 K, 4000 K, 4500 K, and 5000 K), which results in 4 different spectra. From these spectra, taken at 1 m distance just below the center of the surgical luminaire, the corresponding coordinates in \((x, y)\) chromaticity space were checked and complied to the spectral requirements set out by [IEC 2009], as in the left panel in Fig. 1.

Each LED is part of a smaller optical system containing a reflector, a filter and a lens. The focus of the light beam can be varied which results in a smaller or larger light-field size. When referring to the width of the light focus, the letters S (small) and L (large) will be used.

2.2 ANALYTICAL CALCULATIONS USING FAR-FIELD DATA

The illuminance \(E\), measured on a surface, is related to the far-field intensity \(I\) of the light source by [Walsh 1926]:

\[
E(\gamma, \delta, d) = \frac{I(\gamma) \cdot \cos \delta}{d^2},
\]

where \(d\) is the distance from the light source to the receiver, \(\gamma\) is the angle between the normal to the source and the direction of the receiver and \(\delta\) is the
angle between the normal to the receiving surface and the direction of the source. The formula can be evaluated in two ways: a) the illuminance and distance are measured permitting the far-field intensity to be calculated [Stan
nard 1990, 1992], or b) the far-field intensity is measured in a near-field goniometer which allows to calculate the illuminance at any distance from the light source [CIE-70 1987]. The right panel in Fig. 1 shows the far-field intensity for the surgical luminaire used in this paper.

However, applying (1) to these far-field measurements leads to erroneous predictions of the illuminances. Figure 2 proves that illuminances calculated on a task surface 1 m below the light source (Fig. 3) do not correspond to illuminances obtained by a photometer. The difference between analytically calculated and measured illuminances can be explained: (1) is valid for point-like light sources, or sources located at sufficient distance, so that the luminaire can be approximated by a point source. Literature suggests this distance is at least 5 times the size of the luminaire under consideration, but indicate this distance could even increase depending on the intensity distribution [Moerman 1981]. Anyhow, adopting the previously mentioned rule-of-thumb leads to a minimum distance of 3.9 m for (1) to be valid, as the diameter of the luminaire is 0.78 m. Clearly, the mismatch between measured and calculated illuminances proves (1) is inadequate to calculate realistic illuminances in the surgical site at 1m distance and moreover, this will prohibit testing for compliance to [IEC 2009].

Fig. 1. Left panel: The spectral measurements indicate the surgical luminaire complies to the European Standard, which delimiters a region wherein the coordinates should lie (dark gray area). Right panel: the far-field intensity of the surgical luminaire under consideration is used to calculate illuminances in the task plane 1 m below the luminaire.

Fig. 2. The difference between analytical calculations of the illuminance distribution from experimentally obtained illuminances by a photometer, clearly indicates the need for a different approach.
2.3 THE USE OF RAY DATA TO OBTAIN ILLUMINANCES

To obtain realistic illuminances at a distance of only 1 m below the surgical luminaire, near-field techniques will be used in this paper. Angular- and spatially-resolved ray-data of the individual light sources (for example, LEDs) of a surgical luminaire are provided by the manufacturer and can be used to design a virtual prototype of a surgical luminaire.

Ray files obtained by a near-field goniometer allow calculating illuminances in the work space of the surgeon [Jacobs 2012; Van Giel 2012]. A near-field goniometer rotates a luminance camera on a virtual spherical-surface surrounding the centrally-mounted surgical luminaire, with the camera pointed towards the luminaire. A series of luminance images is taken, processed and stored [Bredemeier 2005]. The geometry of the luminaire (the shape and dimensions) is unknown to the near-field goniometer. To construct ray data, the user has to specify the geometry of the luminaire to the software. In accordance to the shape of the surgical luminaire, a cylinder with a diameter of 78 cm is chosen to envelope the luminaire and all rays emerge from the bottom of this cylinder, which corresponds to the light-emitting surface of the surgical luminaire. The software generates a ray file; a list of rays characterized by a starting spatial point (defined by the $x$, $y$, and $z$ coordinates on the emitting surface, a direction ($\phi$, $\varphi$) and an associated radiant flux $\Phi$, that may depend on wavelength $\lambda$ if spectral information is gathered:

$$\Phi(x, y, z, \phi, \varphi, \lambda).$$

(2)

These data were used for ray tracing in the optical simulation software TracePro (http://lambdares.com/). Thereafter, the light distribution in the surgical site
can be analyzed. The surgical site is modeled by a virtual plane 1 m below the light source. (Fig. 3) The light-field center is defined as the center of the plane, that is, the point just below the luminaire. The illuminance on this plane is calculated from the number of rays striking it. To calculate the illuminance on a small area at a specific location \((r, \theta)\) in this plane, that plane is divided in a grid of square cells or pixels. (Fig. 4) To compare these to values obtained by a photometer, we sum over a subset of pixels, so that the total surface matches the area of the photometer’s diffuser \((\varnothing = 7 \text{ mm})\).

3 RESULTS

This section shows that simulated illuminances based on ray data and a virtual model correspond well to experimental illuminances determined by a photometer for all photometric experiments outlined in [IEC 2009]. It shows that performance indicators derived from the illuminance distribution also correspond. These performance indicators are: a) central illuminance, b) remaining central illuminance for various scenarios, c) light-field size, and d) depth of illumination.

3.1 CENTRAL ILLUMINANCE AND ILLUMINANCE DISTRIBUTION

The central illuminance \(E_c\) is defined in [IEC 2009] as the illuminance at 1 m distance from the light source, in the light-field center, in the absence of any obstacles blocking the light beam. According to the European Standard, the central illuminance is restricted to lie within a range from 40 to 160 klx and has to be specified by the manufacturer. When moving outward from the light-field center the European Standard [IEC 2009] requires the illuminance to decrease. Based on simulations, a central illuminance of \(156.0 \pm 5.0\) klx and \(56.8 \pm 1.9\) klx is found for the small and large light-field size respectively. These values are verified by a photometer and correspond well (Fig. 5).

To determine the illuminance distribution at various radii \(r\) from the light-field center, an average illuminance of 8 points was calculated in accordance to the European Standard (Fig. 4). These 8 points all lie at a circle with radius \(r\) from the light-field center and are distributed along this circle with an angular spread.
of 45 degrees. For each distance \( r \), ranging from 0 mm to 220 mm in steps of 10 mm, an illuminance is determined.

The errors on the simulated illuminances are calculated from:

\[
\Delta E_{\text{sim}} = \frac{3 \cdot s(E_{\text{sim}})}{\sqrt{n}},
\]

where \( n \) denotes the 8 points used to determine the simulated illuminance and \( s(E_{\text{sim}}) \) is the standard deviation of these illuminances. A comparison is made to illuminances obtained by a photometer. In accordance to the simulations, an average illuminance of 8 points is calculated for each distance \( r \) from the light-field center. According to the specifications of the photometer, the accuracy is 3.2 percent.

The illuminance decreases when moving outward from the light-field center, in accordance to [IEC 2009]. Figure 5 compares measured and simulated illuminances, each normalized to the central illuminance measured by the photometer for the respective light-field focus.

In sharp contrast to the mismatch that resulted from analytical calculations, this agreement clearly indicates this method is valid to estimate illuminances close to the light source and validates a first virtual photometric test to check for compliance to [IEC 2009].

3.2 PERFORMANCE INDICATORS FOR THE LIGHT-FIELD SIZE

From the illuminance distribution in the previous subsection, the size of the light beam can be parameterized. The European Standard defines two parame-
ters that characterize the shape of the light-field: \( d_{50} \) and \( d_{10} \), where the illuminance reaches resp. 50 percent and 10 percent of the central illuminance \( E_c \). The standard requires that \( d_{50} \) shall be at least 50 percent of the light-field diameter \( d_{10} \):

\[
d_{50} \geq 0.5 \cdot d_{10}.
\] (4)

which assures that the illuminance does not fall off too rapidly when moving outward from the light-field center.

These performance indicators correspond exactly in simulations and measurements: for the small light-field size, \( d_{50} = 4 \) cm while \( d_{10} = 7 \) cm and for the large light-field size, \( d_{50} = 9 \) cm, while \( d_{10} = 14 \) cm, so these values comply to (4).

### 3.3 Remaining Central Illuminance When the Light is Partially Blocked

A method to evaluate shadow dilution is defined in [IEC 2009] by means of masks and a tube (Fig. 3). Various scenarios are described that mimic clinical situations in which light is blocked. The masks obstruct the light, which casts shadows on the surgical site and reduces the central illuminance. This can be caused by the hands or the head of the surgeon. A second mask represents the influence of a surgical assistant. A tube models a deep wound, which also reduces the central illuminance. The European Standard requires manufacturers report on the remaining central-illuminance in the following 12 situations:

L and S 00: the beam is unobstructed,
L and S 01: the beam is obstructed by one mask,
L and S 02: the beam is obstructed by a pair of masks,
L and S 10: the beam is obstructed by a tube,
L and S 11: the beam is obstructed by one mask and a tube, and
L and S 12: the beam is obstructed by a pair of masks and a tube,

where L and S denote the light-field size (large or small), the first number denotes the presence of a tube and the second number indicates the amount of masks in place. All measurements involving two masks will specify the average value of four measurements, where the pair of masks is placed in four successive positions, each 45° apart. The reduction on the central illuminance can be determined in each scenario and has to be reported by the manufacturer.

In all clinically relevant scenarios, illuminances based on simulations correspond well with illuminances obtained by a photometer (Table 1): relative differences between simulations and measurements for the central illuminances deviate maximally 5.6 percent (± 2.2 percent). Again this agreement proves the usefulness of this method, even in more complex situations where reflections are taken into account. Moreover, the proposed virtual method is more time-efficient compared to measurements by a photometer.

Finally, it has been suggested that the section on light-field diameters in [IEC 2009] is not sufficient to assure qualitative lighting: the light-field could for example be rather elliptic than circular, especially when two masks block the light of the beam [Knulst 2009a]. Variations in the illuminance distribution are not covered in [IEC 2009], but occur when \( d_{10} \) and \( d_{50} \) vary in different directions. Using the virtual method proposed in this paper, the illuminance distribution in every point of a plane at 1 m distance is known and a method to parameterize this distortion can be proposed. The technique is first illustrated on hypothetical dataset and then applied to the surgical luminaire. The left panel in Fig. 6 shows a normalized illuminance distribution of an elliptical and slightly...
deformed light-field. The right panel displays various horizontal cross-sections of the distribution in for 5 curves with illuminances ranging from 10 percent to 50 percent of the central illuminance. When the light-field is not perfectly circular, these cross-sections become elliptical. As shown in Fig. 6, ellipses are fitted to each of these curves of equal illuminance and an eccentricity (\(\xi\)) can be derived from the equation of the ellipse:

\[
\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1 \Rightarrow \xi = \sqrt{1 - \left(\frac{b}{a}\right)^2},
\]

Good agreement has been found for measured and simulated central illuminances for twelve various scenarios prescribed by the European Standard.

| Scenario | Measured Illuminance \(E_m\) [klx] | Measured Procentual ratio to \(E_m\) [%] | Simulated Illuminance \(E_m\) [klx] | Residuals \(\frac{|E_{\text{sim}} - E_m|}{E_m}\) [%] |
|----------|---------------------------------|---------------------------------|-------------------------------|---------------------------------|
| L00      | 56.8 \(\pm\) 1.9              | 100.0 \(\pm\) 3.2              | 57.0 \(\pm\) 0.3              | 0.4 \(\pm\) 0.2 \(\pm\) 0.3 |
| L01      | 42.8 \(\pm\) 1.4              | 75.4 \(\pm\) 2.5              | 41.7 \(\pm\) 0.3              | 2.0 \(\pm\) 2.0 \(\pm\) 2.3 |
| L02      | 29.3 \(\pm\) 1.0              | 51.6 \(\pm\) 1.7              | 27.9 \(\pm\) 0.9              | 2.5 \(\pm\) 2.2               |
| L10      | 47.3 \(\pm\) 1.6              | 83.3 \(\pm\) 2.7              | 50.0 \(\pm\) 0.3              | 4.2 \(\pm\) 2.7               |
| L11      | 34.4 \(\pm\) 1.2              | 60.6 \(\pm\) 2.0              | 35.7 \(\pm\) 0.2              | 2.3 \(\pm\) 2.0               |
| L12      | 22.1 \(\pm\) 0.8              | 38.9 \(\pm\) 1.3              | 23.4 \(\pm\) 0.8              | 2.4 \(\pm\) 1.7               |
| S00      | 156.0 \(\pm\) 5.0             | 100.0 \(\pm\) 3.2             | 156.5 \(\pm\) 0.4             | 0.3 \(\pm\) 3.2 \(\pm\) 2.4 |
| S01      | 119.1 \(\pm\) 3.9             | 76.4 \(\pm\) 2.5              | 117.3 \(\pm\) 0.4             | 1.1 \(\pm\) 2.4 \(\pm\) 1.1 |
| S02      | 85.1 \(\pm\) 2.8              | 54.6 \(\pm\) 1.8              | 76.5 \(\pm\) 2.3              | 5.6 \(\pm\) 2.2               |
| S10      | 109.8 \(\pm\) 3.6             | 70.4 \(\pm\) 2.3              | 118.0 \(\pm\) 0.2             | 5.3 \(\pm\) 2.3               |
| S11      | 80.1 \(\pm\) 2.6              | 51.4 \(\pm\) 1.7              | 86.3 \(\pm\) 0.3              | 4.0 \(\pm\) 1.7               |
| S12      | 54.9 \(\pm\) 1.8              | 35.2 \(\pm\) 1.2              | 57.9 \(\pm\) 1.8              | 1.9 \(\pm\) 1.2               |

**Fig. 6.** From the 3-D normalized illuminance-distributions the eccentricity of the light-field can be derived for a hypothetical dataset (upper panels) and the surgical luminaire (lower panels). The elliptical fitting is illustrated in the upper right panel: red ellipses are fitted to the colored curves of equal illuminance, from which the eccentricity can be mathematically derived.
where $a$ and $b$ are the semi-major and semi-minor axis of the ellipse. The lower panels in Fig. 6 display the 3-D normalized illuminance distribution of the surgical luminaire under consideration and reveals the light-field is rather circular. Table 2 confirms that the illuminance distribution of the surgical luminaire has a low eccentricity, even in the presence of masks.

### 3.4 DEPTH OF ILLUMINATION

The depth of illumination is defined in [IEC 2009] and determines the working distance just below the light-emitting surface, in which the illuminance reaches at least 60 percent of the central illuminance. Two points meeting the 60 percent-level will be found: one above and one below the light-field center. The distance between these two points defines the depth of illumination. Based on our simulations, the 60 percent-level was achieved at $61.5 \pm 0.5$ cm and $123.5 \pm 0.5$ cm, thus resulting in a depth of field of $62 \pm 1$ cm. This corresponds with photometric measurements where the 60 percent-level was achieved at $61.5 \pm 0.1$ cm and $122.9 \pm 0.1$ cm, from which a depth of illumination can be calculated of $61.4 \pm 0.2$ cm. This final quality check again indicates the strength of this method to validate compliance to IEC 2009 based on simulations.

### 4 CONCLUSIONS

A cost- and time-effective method was needed to test whether a virtual prototype of a surgical luminaire complies to [IEC 2009]. The European Standard describes how to measure illuminances in three experiments. Traditionally, illuminances are calculated analytically from far-field intensities, but we have shown in this paper that these calculations lead to erroneous predictions, that do not correspond to photometric measurements. Therefore, they are of no use when testing for compliance to the European Standard.

In contrast, it was shown that simulations in which the light source is characterized by angular and spatial luminance data, that can now be obtained by a near-field goniometer, can predict if a luminaire complies to [IEC 2009]. Good agreement was found to measurements by a photometer in three experiments. First, the spatial illuminance distribution in a working plane at 1 m distance from the surgical luminaire was determined. The central illuminance and light-field diameter were derived and were found to comply to [IEC 2009]. Second, various scenarios outlined in the European Standard that mimic clinical situations, in which light from the surgical luminaire is blocked, were successfully simulated based on a virtual model, where masks represent the head or hands of the surgeon and his assistant, and a test tube represents a deep wound. A good impression of the reduced illuminance in various scenarios was achieved. Third, our simulations lead to a correct depth of illumination of a surgical luminaire.

Angular- and spatially-resolved ray-data of individual light sources (for example, LEDs) are currently available on the websites of most LED-manufacturers or

<table>
<thead>
<tr>
<th>Focus of the light beam</th>
<th>0 masks</th>
<th>2 masks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small light-field</td>
<td>$0.08 \pm 0.02$</td>
<td>$0.174 \pm 0.007$</td>
</tr>
<tr>
<td>Large light-field</td>
<td>$0.111 \pm 0.008$</td>
<td>$0.20 \pm 0.02$</td>
</tr>
</tbody>
</table>
even implemented in optical simulation software. These can be inserted in an optical system, composed of combinations of lenses and reflectors to design new and improved surgical luminaires and generate the required angular and spatial luminance data. With these data, the luminaire can be tested for compliance to [IEC 2009] at the design phase, before being assembled and produced. This approach will lead to a more efficient process of developing surgical luminaires.

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