Challenges when designing LED-based illumination systems for medical applications
Content

• Introduction

• Project EDISON
  - measurements of light sources and endoscopes
  - analysis of intensity losses
  - optical simulations

• Illumination optimised according to reflection properties of human tissues

• Project Wound Healing
Lighting Technologies in the Black Forest
State of the Art – Light Sources

- LEDs are systematically replacing Xenon and Halogen lamps in medical devices
  - produce less heat and their spectral emission in the visible range can be tuned

- LED selected with high Ra, mostly R9 (blood) or R13 (skin)
  - but optical properties of biological tissues vary and may be highly reflective (fat),
    highly absorptive of blue/green light (blood) or may have fluorescent properties
    (collagen)

- Very few LED-based tunable illumination units available
  - selection criteria of wavelength filtering are not scientifically based

Quelle: KARL STORZ; Highlights 2016 - Telepräsenz Bildgebende Systeme, Dokumentation,
Beleuchtung, Gerätewagen: "Innovative Visualisierungsmodi in 2D und 3D"; 2016
Aim: enhancing efficiency while reducing the volume of the fiber optics inside the endoscope

Standard illumination optics in rigid endoscopes will be redesigned and optimised taking into account constructive and production related boundary conditions.
Edison: Project development

Analysis of the optical interfaces and losses

Prototype measurements

Optical simulations/optimisation
Equipment:

- Fiberoptic is connected to light source and endoscope
- Endoscope is fixed into auxiliary adapter and mounted on the integrating sphere
- Measurements are performed with an integrating sphere (\(\varnothing=25\,\text{cm}\)) and a spectrometer from GL optics

**Rigid endoscope with external light sources**
Objectives and measurements

Objectives:
• Identify losses bending the fiber optics inside the endoscope
• Identify losses between the light source input and the endoscope output
• Analyse three different light sources (a,b,c) and three endoscopes

Parameters:
• Illuminance
• Color Temperature
• XY-Chromaticity Coordinates

Parameters extracted from the protocol
Measurements: Intensity losses

<table>
<thead>
<tr>
<th></th>
<th>Reference Light Source</th>
<th>Endoscope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1</td>
<td>10216</td>
<td>1877</td>
</tr>
<tr>
<td>Level 5</td>
<td>37218</td>
<td>6878</td>
</tr>
<tr>
<td>Level 10</td>
<td>64308</td>
<td>11827</td>
</tr>
</tbody>
</table>

Brightness Loss [%]

- Level 1: 81.63%
- Level 5: 81.52%
- Level 10: 81.61%
Measurements: Intensity losses

Analysis of additional endoscopes (state of the art)

Overall ca 80 % of the light source intensity is lost before leaving the endoscope!
Measurements: Chromaticity

All endoscopes demonstrate a similar shift changing the brightness levels.
Measurements – Fiber bundle

Are intensity losses caused by bending the fiber bundle?

Analysis of the same fiber bundle used to transport light through the endoscope

- Measurements of the fiber bundle are performed by holding the fiber straight and wrapped around middle and index finger twice

- 20 measurements are carried out for each brightness level

→ NO perceivable changes in intensity or chromaticity shift
Measurements – Fiber bundle

- Results only show minor (negligible) changes (measurement inaccuracies <4 %)
- 10 measurements per bar are carried out

<table>
<thead>
<tr>
<th>Brightness Level</th>
<th>Straight</th>
<th>Wrapped</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1</td>
<td>1942</td>
<td>1924</td>
</tr>
<tr>
<td>Level 5</td>
<td>6898</td>
<td>6833</td>
</tr>
<tr>
<td>Level 10</td>
<td>11323</td>
<td>11181</td>
</tr>
</tbody>
</table>

![Illuminance - Fiber Bundle](image)
Measurements – Light Sources

Very different spectral distribution (CCT, Ra, R9 etc..)

Light Source (a)

Light Source (b)

Light Source (c)
Measurements – Chromaticity light sources

- Stronger x-shift for RGB-light source and high scattering for smaller brightness levels
Measurements – Chromaticity light sources and endoscopes

CIE XY-Chromaticity: Light Source (b) – Endoscopes (a), (b) and (c)

Bigger scattering for lower brightness levels of RGB-light source
Optical simulations

Analysis of all critical interfaces for light coupling and transport

Software LightTools (Synopsis®)
Intensity and uniformity of the light coupling is very much dependent on the light curve distribution (LCD) of the light source.
Optical simulations – Light transport

Simulation of fiber bundle: Geometry and optical transmission properties

Less than 3% of the input light is absorbed in the 300 mm length.
Reflection properties of human tissues

- Physical interaction between light and human tissue is complex
- Only reflected light will be captured by a camera system or directly seen by the surgeon
- Reflection properties of the target tissues and their environment must be known
- Color and intensity contrast can be optimised

\[ C(\lambda) = \frac{R_m(\lambda)}{R_b(\lambda)} \]

Color contrast \( C(\lambda) \) optimised

Development of a multispectral illumination units which spectral characteristics can be flexibly adapted to the specific diagnostic procedures

Measurements of bidirectional reflection distribution functions (BRDF) of representative biological tissues

- EX-vivo? IN-vivo?
- How to categorize human tissues? (liver, lung, nerves, fat)

Prototype of an automated photobiomodulation treatment device for in vitro wound healing studies

Jacquelyn Dawn Parente, Knut Möller, Paola Belloni, Margareta Müller
Chronic wounds are a healing process dysfunction

3+ months
Pressure ulcer
Venous leg ulcer
Diabetic foot ulcer

In Germany (2014)
800K diagnosis
200K new diagnosis
500K treated

FOCUS: Light therapy re-activates healing processes

**Light (LED or LASER)**

**Photobiomodulation**

Wavelength-dependent absorption at mitochondria.

Prototype of an automated photobiomodulation treatment device for in vitro wound healing studies

Treatment parameter reporting is unverified

**Literature reporting (2015)**

1) Wavelength
   - 3% no 'medicine'

2) Irradiance [mW/m^2]
   - 43% no 'dose'

3) Exposure Time
   - 16% no 'protocol'

**Advanced wound care**

- Optimal treatment parameters: *unknown*
- Standard protocols: *none*
- Combinations (light + mechanical + electrical): *none*

**APPROACH: Modeling + control of the wound system**

<table>
<thead>
<tr>
<th>Treatment device</th>
<th>Wound model</th>
<th>Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONTROLLER</td>
<td>SYSTEM</td>
<td>SENSOR</td>
</tr>
</tbody>
</table>

- **System input**
- **System output**

- Error
- Closed wound REFERENCE
- Measured output

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Prototype of an automated photobiomodulation treatment device for in vitro wound healing studies

Prototype device: adjustable treatment parameters for automated and repeatable in vitro experiments.

**LED Board:** Independent control of LED

**Driver Board:** LED dimming

**USB Controller:** Treatment schedule

- Prescribed parameters: Wavelength, Irradiance, Time
- Performance: Uniform treatment delivery to target surface
- Prototype: 2x2 RGB LED array (Results presented)
Prototype of an automated photobiomodulation treatment device for in vitro wound healing studies

Prototype: Updated LED board and Arduino controller

- RGB LED wavelengths
- Uniform irradiance
- Programmable schedules
- Functional in incubator !!!
Irradiance measures [mW/m^2] at intensity settings.

1) Spectral irradiance

LED dimming (PWM method) does not alter wavelength.

2) Integrated irradiance

Measurements determine device emission, but not tissue absorption....
Prototype of an automated photobiomodulation treatment device for in vitro wound healing studies

Ongoing studies to establish dose-response relationships to guide wound healing therapy

Thank you for your attention