# Thermal effects of white light illumination during microsurgery: clinical pilot study on the application safety of surgical microscopes

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**Abstract.** Modern operating microscopes offer high power illumination to ensure optimal visualization, but can also cause thermal damage. The aim of our study is to quantify the thermal effects *in vivo* and discuss conditions for safe use. In a pilot study on volunteers, we measured the temperature at the skin surface during microscope illumination, including the influence of anaesthesia and the effects of staining, draping, or moistening of the skin. Irradiation within the limit given by safety regulations (200 mW/cm$^2$) results in skin surface temperature of 43 °C. Higher intensities (forearm 335 mW/cm$^2$, back 250 mW/cm$^2$) are tolerated, resulting in reversible hyperaemia. At a very high illumination intensity (750 mW/cm$^2$), pain occurs within 30 s at temperatures of 46 °C±1 °C (hand and forearm), and 43 °C±2 °C (back), respectively. Anaesthesia has no distinct effect on the temperature, whereas staining and drapes result in much higher temperatures (>100 °C). Moistening at practicable flow rates can reduce temperature efficiently when combined with a light absorbing and water absorbent drape. In conclusion, surgeons must be aware that surgical microscope illumination without protective means can cause skin temperatures to rise much above pain threshold, which in our study serves as a (conservative) benchmark for potential damage. 
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## 1 Introduction

Modern operating microscopes offer intense xenon light sources for bright illumination with a spectrum similar to daylight. Bright illumination is required due to working in deep channels and at high magnifications. Only with sufficient light can surgery be precise and effective. For that reason the manufacturers of surgical microscopes offer high power light sources up to 300 W.[1–3] Using a lamp power in this range and collimation optics, irradiance at the surgical site can reach almost 1 W/cm$^2$ in the spectral range of 400 to 700 nm. Such high intensity irradiation will heat up the tissue and can result in thermal injury. The affected tissue is not necessarily in the operating field, which is under permanent observation and frequently flushed by NaCl solution. Special attention should be paid to the skin surrounding the wound. This skin might be irradiated for a long time, up to several hours. Because the perilesional skin is closer to the surgical microscope lens, irradiance here might be even higher than in the operating field (Fig. 1). Furthermore, the heating effect could be intensified by foils or drapes.

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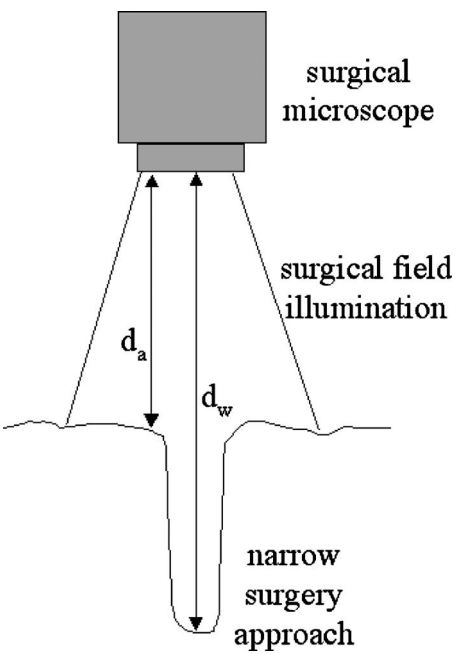


**Fig. 1** Illumination situation in surgery with narrow approaches.

Although being of great importance for the daily clinical use of operating microscopes, there is little information about the thermal effects of surgical microscope irradiation in the literature (Medline and Scopus™ review).[4,5] Several studies provide data about damage thresholds or maximum permissible exposure (MPE) values, but they are related to laser irradiation.[6–8] MPE values for skin, as listed in the International Electrotechnical Commission (IEC) or the American National Standards Institute (ANSI) safety standards for incoherent (lamp) or coherent (laser) irradiation (see Sec. 4), provide a basis to estimate limits for safe use.[9,10] However, there is no MPE value for long-term ($>10$ s) incoherent irradiation of skin. Also, MPE values are derived for employment protection and thus cannot be strictly transferred to surgical procedures. Surgery by its nature is an approved bodily injury for the benefit of the patient, and thus MPE values could be trespassed if advantageous for the quality of the treatment. On the other hand, surgical microscope irradiation levels can exceed the MPE value for laser irradiation of skin by a factor $>5$ (for details see Sec. 4), so that there is a realistic hazard of thermal injury by the use of operating microscopes.

The objective of our investigations was to explore the thermal effects of surgical microscope irradiation under realistic conditions on human skin *in vivo*. The investigations were intended as a pilot study with a limited number of volunteers to characterize general trends and influencing factors to obtain a first estimate of irradiation limits for safe surgical microscope use.

## 2 General Materials and Methods

For our investigations we irradiated the skin of several volunteers (skin types 1, 2, and 3) by the light of an operation microscope. While the volunteers were blinded with respect to the beginning of the irradiation, they were asked to stop it when they perceived the onset of pain. The duration up to this point, and the resulting light dose, respectively, served as a measure to define the limit for safe use. Tissue coagulation might be considered a stricter benchmark for thermal injury, but pain is the natural warning signal and will be closely correlated to it. The assignment of pain instead of coagulation necrosis has the significant advantage that there is no irreversible damage to the skin, so that instead of animal experiments, the tests can be performed under realistic conditions on volunteers. Stoll and Greene showed that the threshold for pain is considerably below the threshold for blistering, but the functional progression of the two thresholds with respect to radiation intensity and time is quite parallel.[11]

During irradiation, skin temperature was monitored by noncontact radiometry, and in some special cases by thermocouples fixed to the skin. Due to depth-dependent absorption and heat dissipation (conduction and convection), temperature will also vary with tissue depth.

According to the penetration depth of the mid-infrared light used for radiometric detection (8 to 14 $\mu$m), temperature measurement with the pyrometer is sensitive to superficial skin (approximately 20 $\mu$m). Please note that pain receptors are located deeper within the dermis, where temperatures could be different from the surface (see also Sec. 4; measurements with a pyrometer and thermocoupler indicate a difference on the order of 1 °C). Temperature measurements with the pyrometer allow us to study the temporal course to temperature elevation, individual differences, as well as the influence of location, blood regulation, and anaesthesia. Furthermore, the measurements give an initial basis to develop a monitoring device for safe application.

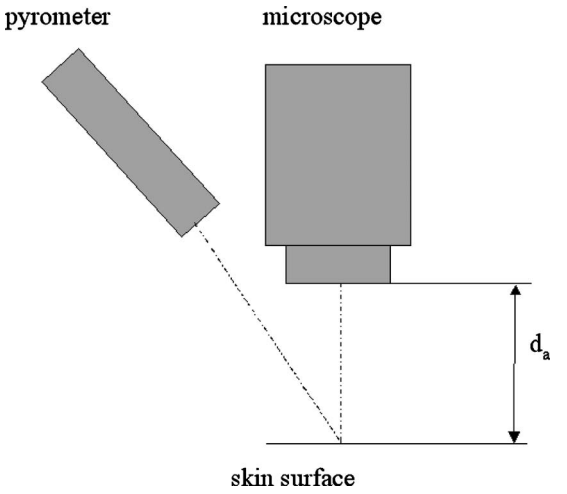


**Fig. 2** Experimental setup.

The general arrangement is depicted in Fig. 2. The test site on the test person's hand, forearm, or back is irradiated by the operating microscope (OPMI Pentero™, Carl Zeiss, Oberkochen, Germany). The skin temperature in the center of the spot was measured continuously by the help of a pyrometer (IN5+, Impac, Frankfurt, Germany), whose output data were stored on a computer. Within a test sequence on various volunteers, the skin surface was positioned at a definite and constant distance from the surgical microscope. To assure a proper measurement, the test persons were asked not to move during the procedure. To partially "blind" the test persons, they were not allowed to observe the test site, and irradiation was started randomly by a second person (operator) after finishing all preparations. Termination, however, was controlled by the test persons themselves via a mechanical shutter. Usually irradiation is followed by a feeling of warmth, which after a while quite rapidly turns into pain. The test persons were asked to stop irradiation at this point. If, in the case of low illumination intensity, this point was not reached, irradiation was stopped by the operator 200 or 300 s after onset.

A summary of all relevant parameters is given in Table 1.

## 3 Results and Discussion

The investigation is a pilot study covering quite a big variety of parameters. Since the number of measurements per parameter is small, a statistical analysis is not appropriate. Wherever adequate, means and simple standard deviations are given.

### 3.1 *General Temperature Behavior*

To identify: 1. the variability caused by the individual test persons, 2. the influence of the test site, and 3. the effect of thermoregulation, we performed investigations on different test persons, each on the back of the hand, the interior forearm, and the back (lumbar vertebra region) with a very low (67 mW/cm$^2$) and higher (265 to 350 mW/cm$^2$) irradiance.

**Table 1** Summary of experimental parameters.

| | |
|---|---|
| Surgical microscope focal length | 200 to 500 mm |
| Working distance ($d_a$, Fig. 1) | 105 mm, 165 mm (volunteers); 213 mm (patients) |
| Percentage for illumination power | 5 to 100% |
| Spatial profile | 90% Gaussian (measured by LBA-100A, Spiricon, Logan, Vtah |
| Spot size | Circular, $1/e^2$ radii: 19 mm ($d_a$ = 105 mm), 24.7 mm ($d_a$=165 mm), 22.2 mm ($d_a$=213 mm) |
| Central irradiance | 67 to 780 mW cm$^{-2}$ (5 to 100% of lamp power) determined prior and after each test series (TPM 310, Gentec, Quebec, Canada) |
| Spectrum | 400 to 700 nm (XE lamp with UV and IR cut-off filters) |

### 3.1.1 *Low intensity irradiation*

For low irradiation, no pain was reported. Typical results of the surface temperature are presented in Fig. 3.

The results show qualitatively comparable temperature profiles for all test persons. Temperature increase is fastest at the beginning of the irradiation and slopes down later, converging to a steady-state plateau. The steady-state, however, is not reached during the tested irradiation of 3 min. Average baseline and maximum temperatures for all test persons are listed in Table 2.

The baseline temperatures, especially of the hand, are quite different among the test persons. The maximum temperatures exhibit approximately the same standard deviation, whereas the temperature increase is the same within a range of less than 1 K for all tested persons. The temperature increase on the back is lower than those measured on the hand and forearm. This indicates stronger heat transport, which might be due to a more pronounced blood perfusion or higher thermal conductivity on the back.

**Table 2** Temperature effect of low intensity (63 mW/cm$^2$) irradiation. Average and standard deviation for six test persons. ($T_0$: baseline temperature; $T_{max}$: maximum temperature (180 s); and $\Delta T$: temperature increase.

| | $T_0$/°C | $T_{max}$/°C | $\Delta T$/°C |
|---|---|---|---|
| Hand | 31.5±2.1 | 34.8±2.3 | 3.3±0.5 |
| Forearm | 32.9±0.6 | 36.2±0.7 | 3.2±0.8 |
| Back | 33.2±1.4 | 35.1±1.3 | 1.9±0.8 |

### 3.1.2 *Medium intensity irradiation*

Results of higher intensity irradiation of the forearm are presented in Fig. 4. Under these conditions, a steady-state temperature is arrived at that increases with intensity [Fig. 4(a)]. Using an irradiation of 335 mW/cm$^2$, a temperature plateau is reached within 2 min [Fig. 4(b)].

While on the forearm no pain was reported, initial tests on the back revealed that 335 mW/cm$^2$ irradiation leads to temperatures above 45 °C and causes pain. Therefore the test series was performed with a lower irradiation (265 mW/cm$^2$) [Fig. 5(a)]. Despite the relatively low intensity, three irradiation programs were aborted because of the onset of pain [Fig. 5(a)]. Comparing the temperature profiles obtained on the forearm and back [Figs. 4(b) and 5(a)], the changeover to the steady-state plateau appears later and is less distinctive for the back. A reason for this might be a less pronounced thermoregulation (in contrast to the higher baseline heat trans-

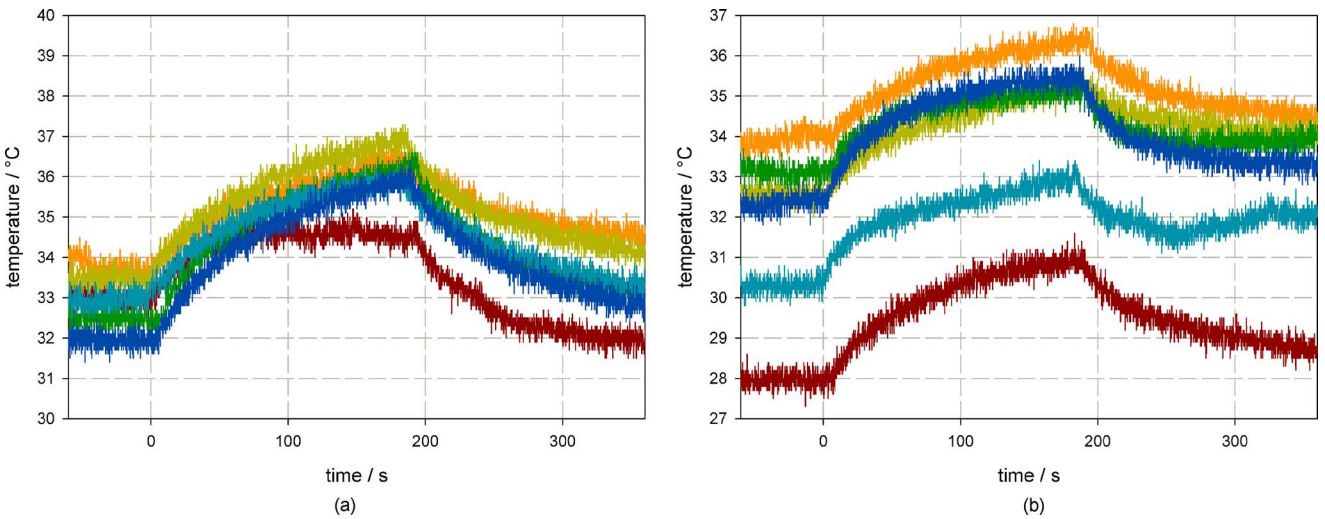


**Fig. 3** Temperature before, during ($0<t<180$ s), and after irradiation with 67 mW/cm$^2$ on the (a) forearm and (b) hand. The different curves represent six test persons.

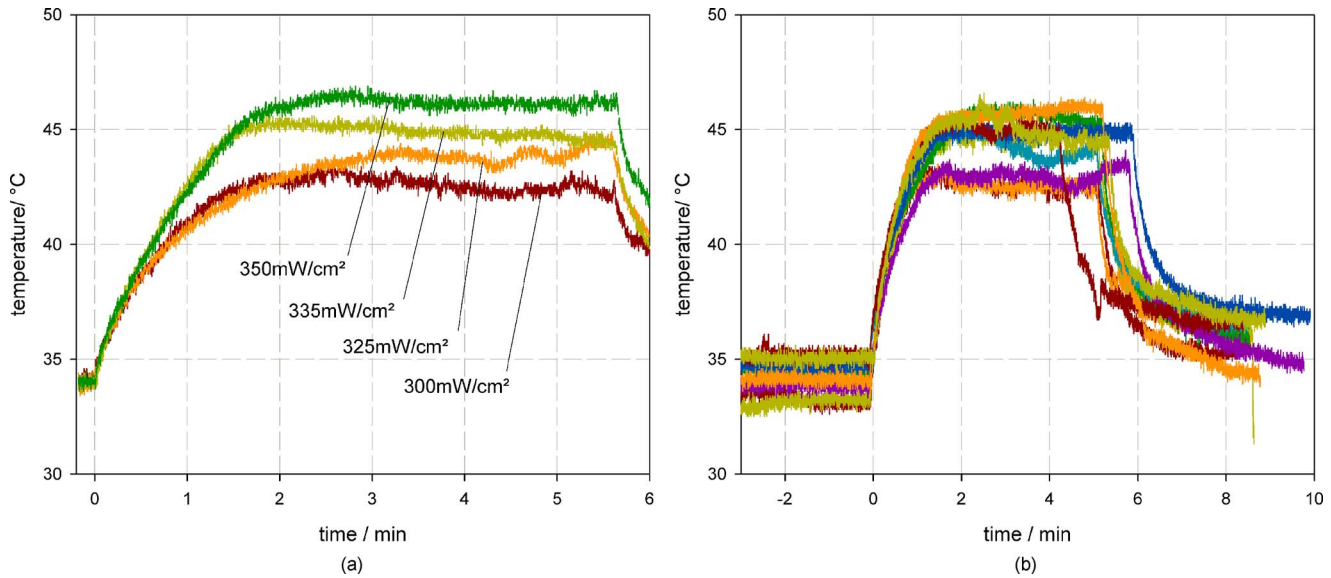


**Fig. 4** Temperature on forearm resulting from medium intensity irradiation: (a) same test person, various intensities, and (b) five test persons, left and right forearm each, 335 mW/cm$^2$.

port). Although a much lower intensity was used on the back, average maximum (=steady-state) temperature increases are quite the same:

- forearm (335 mW/cm$^2$): $\Delta T = 10.1 \pm 1.3$ °C,
- back (265 mW/cm$^2$): $\Delta T = 10.7 \pm 1.0$ °C.

On both locations, the test persons exhibited a redness at the irradiated area, which lasted about 2 to 3 h [Fig. 5(b)].

### 3.2 *Pain Threshold Determination*

To determine the temperature threshold for induction of pain, we irradiated the test sites with a relative high intensity of 750 mW/cm$^2$, which is within the highest operation range of surgical microscopes. The onset of pain was quite distinctively experienced by the test persons. At that moment, they stopped the irradiation.

Results for the hand and forearm are depicted in Fig. 6, together with the skin type of the test persons. Within limitation of the small size of the sample, there are the following observations.

1. The tolerated irradiation is more or less the same for the hand and forearm for an individual person, and quite similar among the group. When irradiation was stopped because of pain, the surface temperature on average reached a level of

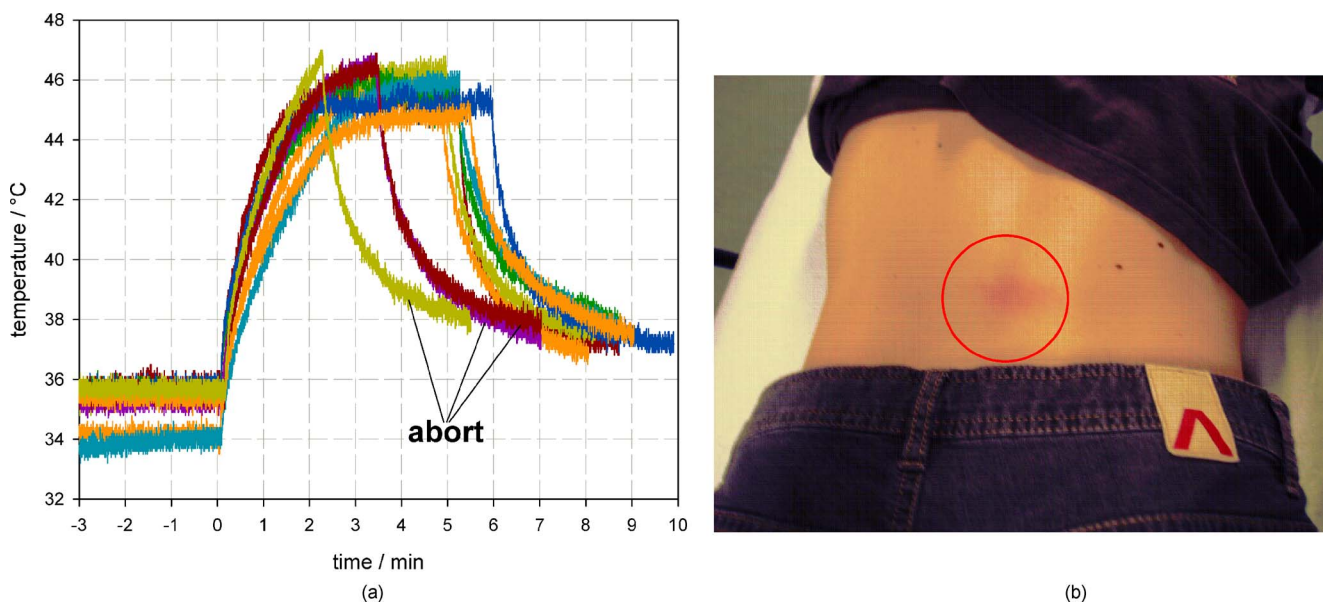


**Fig. 5** Irradiation of the back (265 mW/cm$^2$). (a) Temperature for ten test persons; three tests were aborted because of the onset of pain. (b) Typical redness after irradiation.

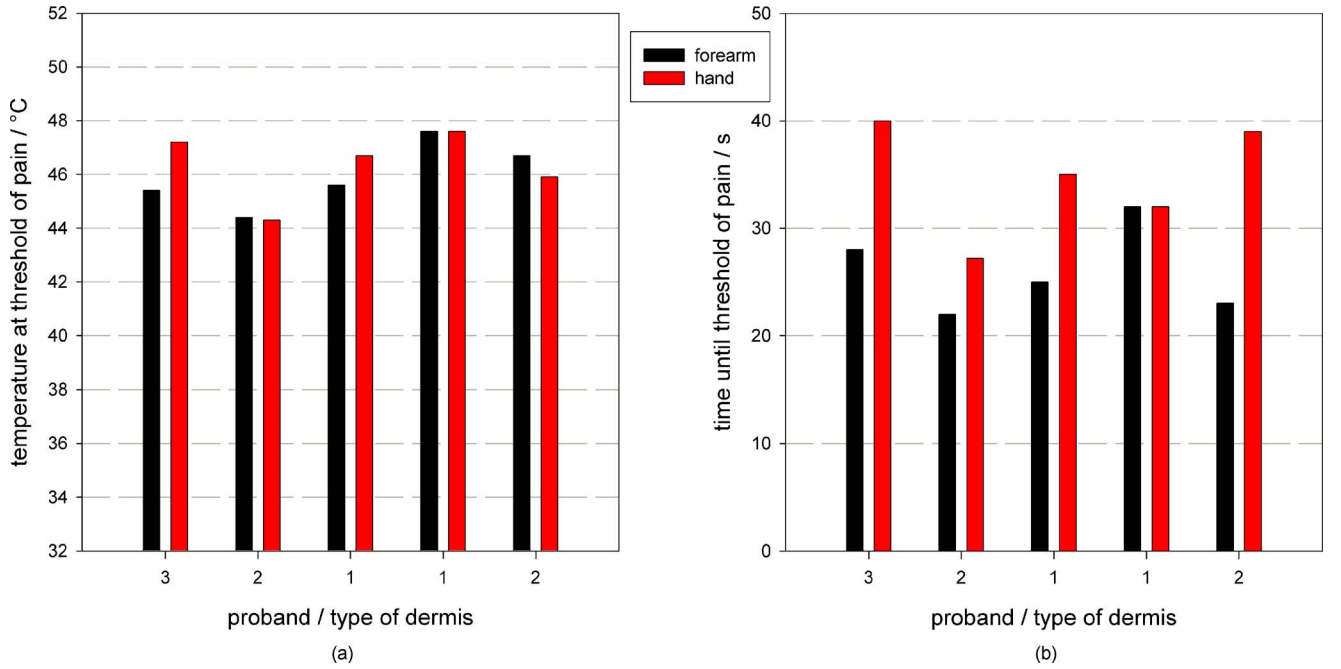


**Fig. 6** Irradiation of hand and forearm (750 mW/cm$^2$). The skin phototype (determined by a dermatologist) is given in the *x* axis. (a) Surface temperature when pain was perceived ($T_{pain}$; five test persons with different skin type). (b) Time until $T_{pain}$ was reached (and irradiation was stopped).

46 °C ± 1.3 °C (surface temperature at pain threshold $T_{pain}$, Table 3).

2. The time until pain is reported, and thus the tolerated light dose, differs between the individuals and the test sites much more than $T_{pain}$. One reason is a variation of the baseline temperature $T_0$. Longer irradiation is tolerated on the hand because of the lower $T_0$ (Table 3).

3. The skin type seems to be of less impact.

In a second series, the same experiment was also performed on the back (lumbar vertebra region) of six test persons. The average results are listed in Table 3. Compared to the results on the hand and forearm, $T_{pain}$ is lower and the variation among the individuals is much larger. Interestingly, the volunteers tolerated slightly higher temperatures when irradiated with lower intensity [see Fig. 5(a)].

### 3.3 *Influence of Anesthesia*

In a normal clinical situation, the surgical microscope is used on anesthetized patients. The studies described before clearly indicate the influence of blood perfusion and thermoregulation on the temperature course. Perfusion and regulation might be reduced by anesthesia. To investigate the transferability of the results obtained for nonanesthetized volunteers onto the clinical situation, we compared the temperature increase for six patients on the same site prior to and during general anesthesia. All patients were regularly scheduled for surgery, the temperature measurements were secondary. In five cases the operations were performed on the hand, and the temperature measurements on the contralateral leg. In one case the operation was on the leg and the temperature measured on the contra-lateral forearm. The parameters of the irradiation are given in Table 4. The intensity was limited to 200 mW/cm$^2$, which is the maximum permissible exposure (MPE) value for laser irradiation in the visible wavelength region (see Sec. 4). As an additional measure for the patient's safety, irradiation was stopped when the skin temperature exceeded 44 °C. This occurred in one case.

As examples, the results for two patients are shown in Fig. 7. In one case the temperature is slightly higher under anes-

**Table 3** Irradiation duration $\tau_{pain}$ and dose for pain perception threshold (750 mW/cm$^2$), and corresponding skin surface temperature $T_{pain}$ ($T_0$: baseline temperature).

| | $\tau_{pain}$/s | dose$_{pain}$/J/cm$^2$ | $T_0$/°C | $T_{pain}$/°C |
|---|---|---|---|---|
| Hand | 34.6±5.3 | 26±4 | 31.5±2.1 | 46.3±1.3 |
| Forearm | 26.0±4.1 | 20±3 | 32.9±0.6 | 46.0±1.2 |
| Back | 39.0±15.9 | 29±12 | 33.3±1.1 | 43.3±2.3 |

**Table 4** Irradiation parameters.

| | |
|---|---|
| Working distance ($d_a$, Fig. 1) | 213 mm |
| Spot size | Circular, diameter 40 mm |
| Central irradiance | 200 mW/cm$^2$<br>determined prior and after each test series |
| Duration of irradiation | 400 s, abort if temperature exceeds 44 °C (one case) |

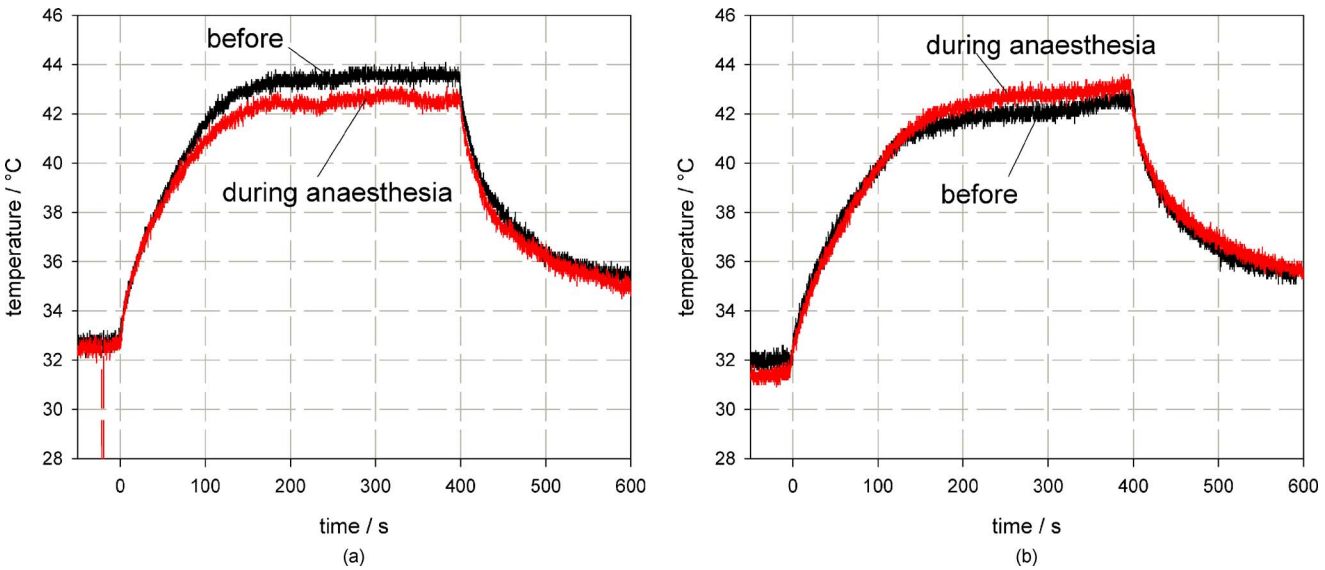


**Fig. 7** Irradiation of patient's leg before and during general anesthesia (200 mW/cm$^2$). (a) and (b) show two different patients.

thesia, in the second it is the other way around. The average results of six patients (Table 5) show no systematic trend. Differences seem not to be prominent in relation to the influence of other parameters, like site or spread among individuals.

### 3.4 *Influence of Iodine Paint and Covers*

During surgery, not only is bare skin illuminated, but also tissue covered by surgical drapes and incision foils, and wiped with iodine paint. In a small sample of three test persons, the effects of these circumstances were investigated on the forearms of the individuals.

We chose both a low intensity (67 mW/cm$^2$) with a fixed duration of 200 s, and a high intensity (780 mW/cm$^2$) until the onset of pain. Tested materials were brown iodine paint, transparent self adhesive incision foil, blue plastic drape, and green textile drape. In the case of the drapes, a thermocouple was slightly pressed into the skin, fixed, and tightly covered by the textiles. The thermocouple was located at the center of irradiation to measure the skin/textile interface. To minimize direct absorption, we used home-made thermocouples with a polished, highly reflecting surface. We tested the potential influence of direct absorption by interrupting the illumination. In the case of direct absorption, an instantaneous decrease of the signal is expected, which we did not observe.

The surface temperature of the drapes, as well as the temperature of the incision foil and the painted skin, was measured as usual by the help of a pyrometer. The results are summarized in Table 6 together with the data for normal skin as a reference.

**Table 5** Average maximum temperature increase $T_{max}$ measured on six patients prior and during anesthesia (200 mW/cm$^2$, 400 s) ($T_0$: baseline temperature).

| | $T_0$/ °C | $T_{max}$/ °C |
|---|---|---|
| Pre-OP | 31.9±1.3 | 42.8±1.2 |
| OP | 31.8±2.0 | 43.1±1.1 |

The temperature increase for the incision foil is quite similar to that of normal skin. All other modalities lead to stronger heating of the skin surface. Interestingly, pain sensation occurred at much higher temperatures $T_{pain}$ compared to the standard situation.

The observations can be explained by the changed heating characteristics. The brown iodine paint leads to a stronger absorption of light at the skin surface. This causes a steeper temperature gradient with a higher temperature at the surface. Because temperature receptors are located within the dermis, a higher temperature at the epidermis might be reached before receptors indicate pain. For the drapes, the situation is even more extreme. The textiles absorb a large fraction of the visible light—for the green cloth we determined a transmission of 19%—and are rapidly heated up. As a result, the skin is heated at its surface by heat convection and conduction. In this case, the temperature at the textile/skin interface can be as high as 80 °C to 100 °C before pain is noticed.

In a further experiment with varying distance between green cloth and skin (realized by spacers), we observed only a slight decrease of the skin temperature with increasing distance, whereas the cloth temperature increased strongly (Fig. 8). In contrast to the experiment described before, for these measurements a direct contact between the thermocouple and cloth was avoided (even at the distance 0 mm). In this situation, the energy transfer from the heated cloth to the skin is by convection via air only. Increasing the distance between cloth and skin results in a decreased energy transfer, which causes a decreasing skin temperature and a higher temperature of the cloth. Because the cloth temperature increases with distance, the temperature gradient—and by this also the energy transfer and skin temperature—decreases only moderately with distance, as observed.

**Table 6** Temperature increase $T_{max}$ and pain threshold temperature $T_{pain}$ for several conditions. The asterisk shows that the value exceeds the selected measuring range.

| | 67 mW/cm² | | | 750 resp. 780 mW/cm² | | | |
|---|---|---|---|---|---|---|---|
| | $T_0$/°C | $T_{max}$/°C | $\Delta T_{max}$/°C | $T_0$/°C | $T_{pain}$/°C | $\Delta T_{pain}$/°C | $\tau_{pain}$/s |
| Normal skin | 32.9±0.6 | 36.2±0.7 | 3.2±0.8 | 32.6±0.8 | 45.9±1.2 | 13.3±0.3 | 26.0±4.1 |
| Iodine paint | 30.6 | 35.5 | 4.9 | 31.3 | 50.1 | 18.8 | 49 |
| Incision foil | 32.8±0.3 | 36.1±0.8 | 3.4±0.6 | 32.1±0.1 | 46.8±3.7 | 14.7±3.7 | 32.5±0.8 |
| Blue drape surface | 32.4 | 42.6 | 10.3 | 32.7 | >71.5* | >38.8 | 56.0 |
| Skin below blue drape | 31.5 | 37.4 | 5.9 | 32.0 | 103 | 71.0 | 56.0 |
| Green drape surface | 31.0 | 49.2 | 18.2 | 30.6 | 132.3 | 101.7 | 27.0 |
| Skin below green drape | 30.1 | 43.7 | 13.6 | 29. 4 | 86.2 | 56.7 | 27.0 |

### 3.5 *Influence of Wetting*

It is well known that temperature can be reduced by moistening the surface. Therefore, in a final set of experiments this effect was also investigated for a variety of conditions (see Table 7). Because the skin surface was covered by water and/or cloth, temperature was measured by a thermocouple inserted into the skin, additionally to the measurement by the pyrometer. The thermocouple was placed by a dermatologist with the help of a canula into the interior forearm of five volunteers. The depth of the thermocouple tip was approximately 1 mm, as controlled by ultrasound once at the beginning of the experimental series. For irrigation, sterile isotonic NaCl solution was used. Irradiation was performed at 750 mW/cm² for 300 s unless stopped before by the volunteers because of pain sensation. The irradiated (and moistened) area had a diameter of 50 mm. In total, 29 measurements were conducted (redundancy 1 to 3). The results are compiled in Table 7; one example is demonstrated in Fig. 9.

The results of the control measurements without moistening correspond quite well to the earlier observations. Pain threshold is reached within a few tens of seconds, the according temperatures are again 46 °C at the surface (pyrometer), and a little bit less (45 °C) within the skin (thermocouple). This can be explained by the temperature gradient within the skin. If the skin is covered by a sufficiently thick water film, the pyrometer measures the water temperature. In the case of moistened tissue, the signal will be an average of water and cloth.

The experiments show that wiping with a moist compress or covering with a moist absorbing (green) cloth results only

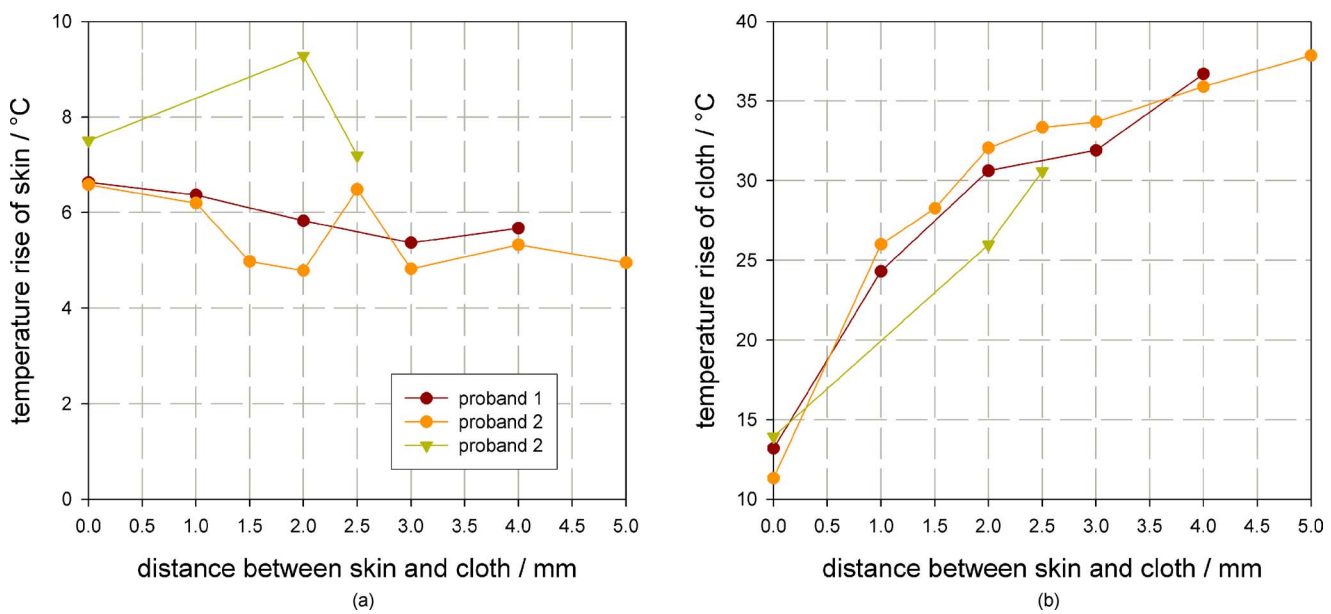


**Fig. 8** Irradiation of skin through a green IO cloth with varying distance (120 mW/cm²): (a) temperature rise of skin surface, and (b) temperature rise of cloth. The cloth was tightened across space holders of different thickness, while the thermocouple was tightly fixed to the skin.

**Table 7** Maximum temperature increase $T_{max}$ during irradiation period (300 s) or at the onset of pain sensation (time $\tau_{pain}$) measured with the thermocouple (inside the skin) and pyrometer. A compress of white, thin tissue paper was nearly clear-transparent when wet; drape and abdominal pack were green. The tissues were either moistened once at the beginning of the irradiation or irrigated by a constant flow of NaCl solution (with the given flow rate; area was 50 mm in diameter).

| | Thermocouple | | | Pyrometer | | | |
|---|---|---|---|---|---|---|---|
| | $T_0$/°C | $T_{max}$/°C | $\Delta T_{max}$/°C | $T_0$/°C | $T_{max}$/°C | $\Delta T_{max}$/°C | $\tau_{pain}$/s |
| Control, without moistening | 33.1 | 44.8 | 11.7 | 34 | 45.9 | 11.9 | 17.2 |
| Wiping with moist compress every 4 seconds | 34.2 | 50.5 | 16.3 | n.a. | n.a. | n.a. | 37 |
| Continuous fluid flow, 100 ml/min | 33.4 | 29.2 | −4.2 | 33.4 | 28.5 | −4.9 | — |
| Fixed moist drape | 33 | 41.9 | 8.9 | 33.6 | 50.4 | 16.8 | 20 |
| Fixed moist abdominal pack | 32.9 | 42.5 | 9.6 | 30.9 | 55.2 | 24.3 | 38 |
| Fixed moist compress | 33.2 | 37.5 | 4.3 | 27.7 | 33.3 | 5.6 | — |
| Thin tissue paper+1 ml/min | 32.5 | 44.9 | 12.5 | 32.5 | 45.5 | 13 | 165/47 |
| Thin tissue paper+2 ml/min | 32.1 | 44.3 | 12.2 | 32.1 | 46.1 | 14 | —/200 /142 |
| Thin tissue paper+3 ml/min | 30.6 | 43.9 | 13.3 | 30 | 45.5 | 15.5 | —/— |
| Abdominal pack+3 ml/min | 30.1 | 37.2 | 7.1 | 30.6 | 41.3 | 10.7 | —/—/— |
| Abdominal pack+5 ml/min | 30.5 | 35.9 | 5.4 | 29.9 | 38.5 | 8.6 | —/—/— |
| Drape+2 ml/min | 30.8 | 40.7 | 9.9 | 30.9 | 46.3 | 15.4 | 40 |
| Drape+3 ml/min | 29.7 | 36.4 | 6.7 | 30.2 | 42.7 | 12.5 | 59/24 |
| Drape+5 ml/min | 31.7 | 36.5 | 4.8 | 29.2 | 44.2 | 15 | — |

in a minor cooling effect, so that the pain threshold is still reached within the irradiation time. A strong fluid flow or a combination of tissue and moderate flow can result in a more or less constant temperature after initial heating (see Fig. 9). Comparing the different covers—thin tissue paper (nearly clear-transparent when being wet), drape, and abdominal pack—the abdominal pack, which is water absorbent, has the best cooling effect. During irradiation of absorbing green tissue (drape, abdominal pack), rising water vapor was observed. Within the tested range (2 to 5 ml/min), the strongest flow was most beneficial.

## 4 Discussion

The aim of our pilot study was to explore a first estimate of illumination limits for safe use of operating microscopes. As a borderline, we used the occurrence of pain, which naturally triggers the adverse-effects reflex but is absent for patients under anesthesia. When heating to this stage, we observed (reversible) hyperaemia, even for the relative short irradiation duration of approximately half a minute, as in our experiment (Table 3).

Within the limitations of our small sample size, we found for the hand and forearm a relatively consistent border surface temperature $T_{pain}$ of 46 °C ± 1 °C. Approximately the same temperature is tolerated also on the back when moderate intensities are applied [Fig. 5(a)]. For high intensity, $T_{pain}$ is lower and less consistent (43.3 °C ± 2.3 °C). These observations correspond to the known sensitivity of dermal receptors. Thermal receptors (fibers of type C) are activated for temperature variations between 30 and 45 °C with a maximal sensitivity between 41 and 45 °C. Above 45 °C, thermal nociceptors are activated so that temperatures above 45 °C are discerned as painful. Additionally, there are polymodal nociceptors, which can respond to sharp and strong mechanical stimulations, but also code for temperature rises above 43 °C as painful.[12] Because irradiation with visible light results in a temperature gradient, epidermal temperature will be slightly higher than the temperature at the receptors located within the dermis.

The irradiation conditions (irradiance/time combinations) resulting in $T_{pain}$ are quite variable. They depend on the individual baseline temperature and especially on the treated site of the body, which influences heat transport (blood perfusion, heat conduction, thermoregulation). The borderline irradiance to cause pain is approximately 335 to 350 mW/cm$^2$ for the forearm, and 250 to 265 mW/cm$^2$ for the back.

These data should be compared with maximum permissible exposure (MPE) values given in safety guidelines. There

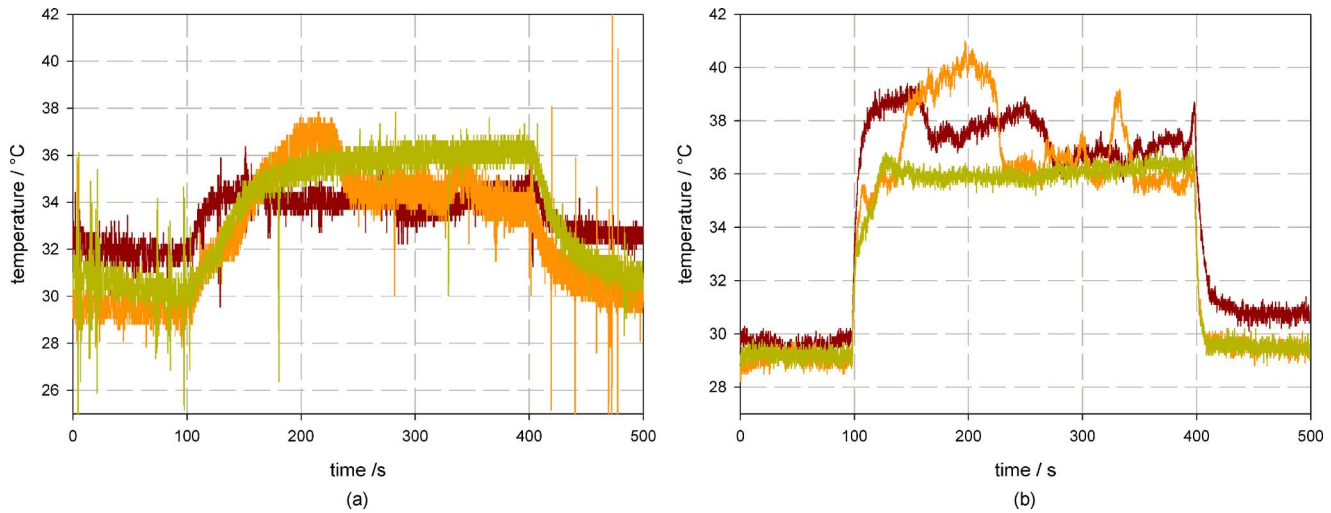


**Fig. 9** Irradiation of skin through a green abdominal pack moistened with a constant flow of 5 ml/min NaCl solution (irradiance: 750 mW/cm$^2$). Temperature was measured with a thermocouple inserted into (a) skin and (b) pyrometer. The different curves represent 3 test persons.

are guidelines for incoherent illumination and laser irradiation.

*Incoherent illumination.* MPE values and incoherent visible/IR illumination are given by IEC 62471:2006 and CIE S009, E:2002 standards for photobiological safety of lamps and lamp systems. They refer to a wavelength range 380 to 3000 nm and an exposure duration t < 10 s. The exposure limits for skin thermal hazards are given by

$$H = 20000t^{0.25}\ \mathrm{Jm^{-2}} \quad \text{(radiant exposure)}, \tag{1}$$

$$E = 20000/t^{0.75}\ \mathrm{Wm^{-2}} \quad \text{(irradiance), respectively.} \tag{2}$$

($t$: exposure duration in seconds, and $t < 10$; 380 nm $\leqslant \lambda \leqslant$ 3000 nm.)

Data from ANSI Z136.1-2000 (400 to 3000 nm) are comparable. In all guidelines there are no MPE values presented for longer exposure durations or for narrowed spectral regions.

When, for an estimate, t = 10 s is adopted, Eqs. (1) and (2) yield

$$H = 3.56\ \mathrm{Jcm^{-2}} \quad \text{and} \quad E = 356\ \mathrm{mW\,cm^{-2}}.$$

*Coherent laser radiation.* Safety guidelines for coherent laser irradiation contain more differentiated MPE values with respect to spectral range and exposure duration. IEC 62471:2006 and ANSI Z136.1-2000 specify the following limits:

$$10^{-7} < t < 10: \quad H = 11000C_A t^{0.25}\ \mathrm{Jm^{-2}}, \tag{3}$$

$$10 < t < 3\ 10^4: \quad E = 2000C_A\ \mathrm{Wm^{-2}}, \tag{4}$$

($t$: exposure duration in seconds.)

The wavelength-dependent coefficients $C_A$ are listed in Table 8.

Comparing Eq. (1) for broadband incoherent irradiation with the corresponding Eq. (3) for coherent irradiation, one notices that the MPE value derived according to Eq. (1) is about twice as high than the respective laser value in the wavelength range <700 nm. On the other hand, it is much lower than the laser MPE for the longer wavelengths (1050 to 1400 nm). The reason appears to be the lower absorption of the near IR radiation compared to the visible, resulting in deeper penetration and less temperature increase within the upper skin regions. Since there is no indication to assume a different thermal response of coherent and noncoherent light, it seems reasonable to rely on the laser standards for durations $t > 10$ s.

So, for the problem of safe surgical microscope illumination in the wavelength range 400 to 700 nm, Eqs. (3) and (4) with $C_A = 1.0$ might give an appropriate reference value, which is 200 mW/cm$^2$. This irradiance can be considered absolutely safe. We used it when we investigated the influence of general anaesthesia on patients. In this case, the average maximum temperature was approx. 43 °C ± 1 °C (Six patients, Table 5). The MPE value of 200 mW/cm$^2$ is much lower than the irradiation provided by modern surgical microscopes (approximately 25% of maximum power) and presumably frequently exceeded in daily use. Of course, application parameters of surgical instruments must not fulfill standards derived for employment protection, and also illumination might infringe MPE values if needed to improve the quality of

**Table 8** Parameters $C_A$ and corresponding Eq. (3) (IEC 62471:2006 and ANSI Z136.1-2000).

| Wavelength range | $C_A$ value | Eq. (3) |
|---|---|---|
| λ < 700 nm | 1.0 | $H = 11000\ t^{0.25}\ \mathrm{Jm^{-2}}$ |
| 700 to 1050 nm | $10^{0.002(\lambda-700)}$ | |
| 1050 to 1400 nm | 5.0 | $H = 55000\ t^{0.25}\ \mathrm{Jm^{-2}}$ |

surgery. In the end, it is the decision of the surgeon how much light he will need and which risk of thermal injury he will accept for this.

Although being a pilot study with a relatively small number of volunteers, our investigation clearly shows differences of the temperature effect depending on the location. Therefore, one hardly can define general limits for irradiance or radiant exposure valid for all patients and regions. Instead, it would be appropriate to monitor the temperature of the perilesional tissue. The maximum permissible temperature could be assessed according to the accepted risk. In our study we set the advent of pain as a borderline and observed hyperaemia but no irreversible damage. So, the risk level next to "generally safe" ($I < 200$ mW/cm$^2$) could be "safe" with the condition $T_{max} < 45$ °C. Here, somewhat higher irradiance can be tolerated (for our test persons $\approx 250$ mW/cm$^2$ on the back and $\approx 335$ mW/cm$^2$ on the forearm). A further limit will be reached with the beginning of tissue necrosis by coagulation.

A potential means to reduce the temperature to a safe level is by moistening. Wiping with a moist compress every 4 s slightly prolongs the tolerable irradiation time, but is not enough to keep the temperature on a safe level. Also, covering the skin with a moist tissue is not very effective, unless it is strongly remitting the light like the white compress. Backscattering surfaces, however, might dazzle the surgeon. Another means of cooling is irrigation with a constant water flow. This has the problem that the water is not homogeneously distributed across the irradiated surface, but tends to form runlets, even on degreased skin. To overcome this, a relative strong water flow (like 100 ml/min used in the experiment) must be scanned across the surface. However, the large amount of fluid might be a practical problem. The preferred practical solution might be covering the skin with an optical absorbing (green) and water absorbent cloth (like the used abdominal pack) continuously moistened by a moderate flow (5 ml/min). By this, a stable temperature, even below the baseline, can be achieved. Presumably here we have two ways of cooling: convection by the fluid flow, and evaporation chill.

## 5 Conclusions

The investigation demonstrates that severe thermal effects on skin can occur by the use of operating microscopes under special conditions (e.g., short working distances, small focused spot size) even at moderate illumination power levels (e.g., 40% of maximum), which would result in pain and not be tolerated if patients would not be anesthetized. Special attention has to be paid when the skin is painted (e.g., with iodine) or covered by drapes or IO clothes. Increased absorption will result in much higher surface temperatures compared to bare skin. We recommend to control the perilesional tissue temperature and to undertake measures to protect the tissue from thermal damage. These could include avoiding unnecessary illumination (spot size and time), cooling by cold fluids, or shadowing by reflecting covers. To avoid high irradiances on the patient's skin, the size of the luminous field should be variable and set automatically according to the magnification-dependent field of view. The light source should have a threshold setting, at which a warning is given to the surgeon when exceeded. But to achieve the best possible success of a treatment, the surgeon should have a optimal sight of the operation field at all times. Nevertheless, intensive warming of the mentioned tissue parts cannot always be avoided.

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