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● *Original Contribution*

EXPERIMENTAL AND NUMERICAL DETERMINATION OF THE LOCAL TEMPERATURE DISTRIBUTION DURING PHACOEMULSIFICATION AND COMPARISON OF DIFFERENT SURGERY SITUATIONS WITHIN ENUCLEATED PORCINE EYES

Steffen Buschschlüter,* Jörn von Eicken,† Christian Koch,* and Helmut Höh†
*Physikalisch-Technische Bundesanstalt, Braunschweig, Germany; and †Klinik für Augenheilkunde, Dietrich-Bonhoeffer-Klinikum, Neubrandenburg, Germany

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Abstract—Phacoemulsification, a common treatment for cataract, is accompanied by cell damage at the corneal endothelium. Thermal exposure during treatment has been considered a reason for this damage, but a thorough experimental and theoretical assessment of the local temperature distribution inside the eye had not yet been conducted. Measurements in porcine eyes and a finite-element simulation enabled such an assessment and localized the highest temperature rise very close to the probe. The results described in this study indicate that a distance of 1 mm between the probe and the endothelium should be maintained during treatment as a safety margin, especially when fluid flow is blocked. The highest measured temperature rise with surgically reasonable system settings and unblocked fluid flow was 1.11°C. The finite-element simulation described here is able to calculate the temperature rise at the endothelium and could serve as a tool for comparing arbitrary surgical situations with respect to thermal exposure of the endothelium. (E-mail: steffen.buschschlueter@ptb.de) © 2015 World Federation for Ultrasound in Medicine & Biology.

Key Words: **Phacoemulsification, Endothelium, Cell damage, Temperature increase, Finite-element simulation.**

INTRODUCTION

Phacoemulsification represents the most common technique for cataract surgery (Dooley and O’Brien 2006). The hollow phacoemulsification probe is made of titanium alloy and fragments the opaque lens inside the capsular bag using ultrasound. The treatment is characterized by a low rate of complications, but post-operative dysfunction or cell loss at the corneal endothelium is well documented in the literature (Ben-Eliahu et al. 2010; Bourne et al. 2004; Zaidi et al. 2007). The corneal endothelium is a cell monolayer between 4 and 6 μm thick on the posterior corneal surface. This cell layer balances the inflow of aqueous humor into the stroma by controlled pumping action. This stromal dehydration maintains the regular thickness and transparency of the cornea (Mishima 1982; Tuft and Coster 1990). Postoperative dysfunction of the endothelium can provoke a reversible corneal swelling or an irreversible bullous keratopathy. To date, no conclusive explanation has been offered for this damage during surgery. In addition to cavitation and contact with lens fragments or instruments, thermal exposure has been reported to be responsible for the damage to the endothelium (Hayashi et al. 1996; Holst et al. 1993; Olson et al. 1978). Temperatures above 65°C have been measured at the corneal incision with an obstructed aspiration line (Mackool and Sirota 2005; Yamagami and Yamagami 1998), which can temporarily occur during surgery because of the lens fragments in front of the phacoemulsification probe. Heisler et al. (2002) measured, with thermocouples, the temperature elevation inside the anterior chamber during 50 surgeries. The temperature rise was below 3°C after sonication in continuous wave mode for 0.3–4.7 s and less than 2°C in pulse mode. However, all these studies obtained temperature data at a certain location in the eye, but key to an assessment of the risk of thermal damage to endothelial cells is knowledge of the temperature rise close to the endothelial cell layer. Furthermore, the distribution of the heat generated inside the anterior chamber by fluid flow is still poorly understood. Amplitude setting, flow rate and duty cycle in the

Address correspondence to: Steffen Buschschlüter, Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany. E-mail: steffen.buschschlueter@ptb.de

pulse mode have been identified as parameters affecting heat transfer and temperature elevation (Braga-Mele 2006; Jurowski et al. 2006; Yamagami and Yamagami 1998), but a thorough understanding of the influence of these system settings has not yet been established.

The purpose of this study was to obtain reliable data on the maximum temperature rise inside the anterior chamber and at the endothelium during phacoemulsification. The influence of fluid flow inside the anterior chamber, amplitude setting and pulse mode on temperature increases deserves to be examined more closely. In the first experiment, the temperature elevation was measured with thermocouples at various positions inside the anterior chamber of porcine eyes to identify those regions with maximum thermal exposure. In the second experiment, four different system settings were compared with respect to temperature change at these previously identified locations. The temperature rise was measured in 20 porcine eyes per system setting. Statistically validated results were obtained because of the large number of measurements performed.

Such experiments with porcine eyes are, however, very time consuming and do not yield the exact temperature at the corneal endothelium. As an alternative approach, the temperature rise inside the eye was calculated numerically using the finite-element method (FEM). This computation was described in a previous study (Buschschlüter et al. 2014) and is based on analytical and experimental quantification of the mechanisms of heat generation during phacoemulsification. Inside the anterior chamber, the oscillating probe induces turbulence and a shear flow within the surrounding fluid. This results in viscous friction among neighboring fluid layers and dissipation of kinetic energy accompanied by heat generation. Electrical dissipation heats the handpiece and, thus, the irrigation fluid, which is flowing through it toward the eye. Finally, absorption of emitted ultrasound inside the anterior chamber and adjacent tissue acts as a heat source resulting in an additional temperature rise. The quantitative description developed provides the magnitude of the heating rate, $\dot{q}_{\text{Phaco}}$, of the phacoemulsification probe and its dependence on system settings (Buschschlüter et al. 2014). Knowledge of $\dot{q}_{\text{Phaco}}$ enabled FEM simulation of the temperature distribution inside the eye without inclusion of sound generation and its propagation. The FEM simulation considered the complex interaction between heat conduction and convection in the eye and delivered the local temperature distribution with a spatial resolution much higher than could be determined by measurements. The same four system settings used in the second experiment were implemented in the FEM model to validate the simulations. The temperature rise at the corneal endothelium was determined by modeling for all system settings used.

METHODS

Temperature measurements were carried out in 85 porcine eyes. Five porcine eyes were used for the first experiment and 80 eyes for the second experiment. Porcine eyes were used because they are easily available and are comparable in dimensions to human eyes. The porcine eyes used for this study were purchased from a slaughterhouse. An angled slit knife with a width of 3.2 mm was used to make a clear cornea incision. In both experiments, the phacoemulsification probe was positioned parallel to the horizontal iris plane, with its tip in the center of the anterior chamber in the bevel-up position (Fig. 1). The conventional phacoemulsification system used was a Megatron (Geuder, Heidelberg, Germany) with coaxial irrigation and aspiration. To be able to compare the results of this study with findings of other studies, the system properties were determined with a laser heterodyne vibrometer (Polytec, Waldbronn, Germany). The operating frequency was $f = 43.0 \pm 0.1$ kHz, and the maximum stroke length, corresponding to an amplitude setting of 100%, was $\xi_{100\%} = 60.0 \pm 1.6$ μm. Thus, an amplitude setting of 50% represents a stroke length of $\xi_{50\%} = 0.5\xi_{100\%}$. Tailor-made temperature sensors were inserted into the anterior chamber to allow time-dependent measurement of the temperature. These sensors consisted of type K thermocouples (Newport Electronics, Santa Ana, CA, USA) with a wire diameter of 50 μm. The thermocouples were encased in a carbon

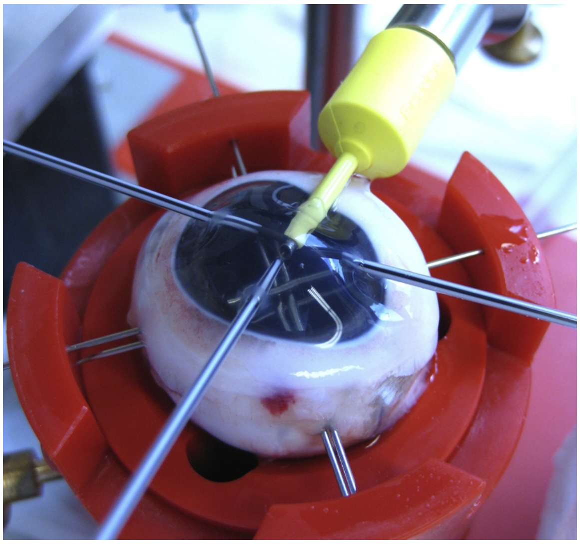

Fig. 1. Photograph of the measurement setup used in both experiments. The porcine eye was fixed by four cannulas, and the phacoemulsification probe was positioned parallel to the horizontal iris plane. Thermocouples were used to measure the temperature elevation inside the anterior chamber. Experiments 1 and 2 differed in terms of the number and position of thermocouples.