Effects of ultrasound energy on the porcine corneal endothelium – Establishment of a phacoemulsification damage model

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ABSTRACT.

Purpose: The purpose of this study was to establish a standardized in vitro phacoemulsification damage model for future investigations of the effects of phacoemulsification, surgical devices, protective ophthalmic viscoelastic devices (OVDs), irrigation solutions and other aspects related to cataract phacoemulsification surgery on the corneal endothelium using porcine eyes.

Methods: Thirty-four porcine eyes were randomly assigned to three groups (phacoemulsification (n = 13), irrigation (n = 9), control (n = 12)). A total of 5 min of ultrasound energy with intermittent irrigation/aspiration was applied in the eyes of the phacoemulsification group. The eyes of the irrigation group received the identical treatment, but without the application of ultrasound energy. The control group was left untreated. All eyes were then prepared to split corneal buttons followed by 15 days of cultivation. Endothelial cell density (ECD) was assessed blinded on day 15.

Results: Endothelial cell density declined significantly more until day 15 in the phacoemulsification group (2567±331/267 cells/mm² (median ± 25%/75%-quartiles), −32.5 ± 7.0/6.4%) compared to the irrigation (3450 ± 350/383 cells/mm², −11.8 ± 5.3/2.6%; p < 0.001) and the control group (3650 ± 288/258 cells/mm², −10.2 ± 3.2/4.6%; p < 0.001).

Conclusion: The phacoemulsification damage model presented in this study is sensitive to phacoemulsification energy and may reliably be used to investigate various factors involved in phacoemulsification with regard to their influence on corneal endothelial cells. This method is able to replace animal experiments or in vitro cell culture experiments that often do not translate well to the in vivo situation in humans.

Key words: cataract – corneal endothelial cells – corneal endothelium – phacoemulsification – research model – ultrasound energy

Introduction

Cataract phacoemulsification is one of the most commonly performed surgical procedures worldwide with the number of surgeries still on the rise (Gollogly et al. 2013; Wang et al. 2016). Concomitant endothelial cell loss (ECL) is one of the main concerns to be respected by cataract surgeons, as phacoemulsification-induced cell damage is among the major causes for later posterior lamellar endothelial keratoplasty (e.g. DMEK) or even penetrating keratoplasty (Dick et al. 1996; Diaz-Valle et al. 1998; Walkow et al. 2000; Morikubo et al. 2004; Storr-Paulsen et al. 2008; Gonen et al. 2012; Keenan et al. 2012; Shimazaki et al. 2014). Numerous studies investigated factors with an impact on the corneal endothelium during cataract surgery, such as ultrasound time and energy, temperature increase, nuclear fragments colliding with the corneal endothelium, firmness of the lens, turbulent flow during irrigation, fluctuating or increased intraocular pressure due to the bottle height of the irrigation solution, surgical instruments and techniques, as well as the formation of free radicals and the use of ophthalmic viscoelastic devices (OVDs) (Svensson & Mellerio 1994; Dick et al. 1996; Hayashi et al. 1996; Pirazzoli et al. 1996; Cameron et al. 2001; Miyata et al. 2002; Takahashi et al. 2002, 2006; Bourne et al. 2004; Storr-Paulsen et al. 2007, 2008; Murano et al. 2008; Suzuki et al. 2009, 2014, 2016; Ho & Afshari 2015).
However, a reliable in vitro model to investigate phacoemulsification-related influences on the corneal endothelium is missing so far. Models used to analyse the damaging effects of phacoemulsification are usually based on in vitro cell culture experiments or on in vivo data from patients or live animal experiments. Cell culture experiments can easily be standardized, but often do not translate well to the in vivo situation. In vivo experiments are very time- and resource-consuming and usually restricted to a special subject of interest due to practical and ethical reasons.

The aim of this study was to develop a reliable and standardized organotypical phacoemulsification damage model to investigate the influences of various aspects of phacodynamics on the corneal endothelium, that is, phacoemulsification energy and protective substances such as ophthalmic viscoelastic devices (OVDs), which closely represents the in vivo situation. Our recently published organ culture model for porcine corneas using split corneal buttons showed an ECL within the first 2 weeks of cultivation comparable to cultivated human donor corneas (Kunzmann et al. 2018). Eyes obtained from pig cadavers were used by numerous studies before, but until recently post-operative stable cultivation over a longer period was not possible due to corneal swelling during longer cultivation; thus, the observation time was restricted to the immediate examination after the preparation and/or intervention (Kunzmann et al. 2018). We combined this previously published organ culture model with prior phacoemulsification to develop a phacoemulsification damage model using pig eyes with stable postoperative-cultivating conditions.

Materials and Methods

Phacoemulsification, irrigation, cornea preparation and tissue culture

Three groups were compared in this study:
1. phacoemulsification group (PHACO; n = 13),
2. irrigation group (IRRIG; n = 9) and
3. control group (CONTROL; n = 12).

Whole porcine eyes (age 6 ± 1 months) were obtained from a local abattoir. All eyes were enucleated prior to thermal disinfection of the pigs and processed within 12 hr after death. Eyes with obvious corneal trauma or other pathologies were discarded. Remaining connective and supportive tissue was removed followed by disinfection of the eye bulps in a 1:20 iodine-PBS solution. Then, all eye bulps were thoroughly irrigated in sterile PBS.

Under sterile conditions, the prepared eye bulps were placed on a bulb holder (Bausch&Lomb, Germany). A single 2.75 mm tunnel incision (ophthalmic slit knife 2.75 mm, Mani, Utsonomya, Japan) was cut at the corneoscleral limbus in the eyes of the phacoemulsification group under a surgical microscope. A 30° phacoemulsification tip covered in a silicone sleeve (Fritz Ruck GmbH, Germany) was inserted carefully into the anterior chamber parallel to the iris to avoid contact to the corneal endothelium and the lens capsule until it reached the pupill’s centre. The anterior eye chamber was irrigated (10 seconds), followed by aspiration of the irrigation solution (10 seconds) and consecutive ultrasound application (10 + 10 seconds pause) in bevel-down orientation of the phaco tip. This procedure was repeated until a total ultrasound time of 5 min (30 cycles, total energy = 1700 J) was applied. A PENTASYS phacoemulsification machine (Fritz Ruck GmbH, Germany) was used for phacoemulsification (ultrasound energy 30%, irrigation 105 cmH2O, aspiration 200 mmHg). Balanced salt solution was used as irrigation substance in all groups. To stabilize the anterior chamber before further preparations, we injected Optimel (viscoelastic (hydroxypropyl methylcellulose), Ophthalmo Pro GmbH, Germany) through the tunnel slit into the anterior chamber.

The irrigation group was treated identically, but without the application of ultrasound. All eyes of the control group were left untreated after disinfection. Several eyes of all three groups were prepared side by side within a preparation cycle.

As described previously, a trephine (ø 7.5 mm, Geuder GmbH, Germany) was used to excise the central cornea (Kunzmann et al. 2018). All corneas were thinned by 300 μm with a standardized inlay inside the trephine prior to complete trephination to remove the epithelium and the upper part of the stroma. For later identification of the endothelial side, a suture (Ethilon 10.0; Ethicon Inc., USA) was inserted on the stromal side of the split corneal buttons.

Histology of the endothelial cell layer and cell count

For the histological examination, the split corneal buttons were transferred into another culture plate containing 3 ml of hypotonic balanced salt solution (hBSS; per 100 ml H2O: NaCl 490 mg; KCl 75 mg; CaCl2 × 2 H2O, MgCl2 × 6 H2O 46 mg, sodium acetate × 3 H2O 390 mg; sodium citrate × H2O 170 mg). The endothelium was analysed with a phase-contrast light microscope (Axiovert 135, Zeiss, Germany) at day 1 and 15 postpreparation. Photographs were taken from the central corneal areas. On day 15, the corneal samples were additionally stained with 0.25% trypan blue (MERCK, Germany) and 0.2% alizarin red S (Merck KGaA, Germany) for 90 seconds each as described previously for later morphological evaluation (Taylor & Hunt 1981). After each staining step, the samples were rinsed three times in a 0.9% sodium chloride solution (Taylor & Hunt 1981).

Photographs of the endothelium were processed with AxioVision4.6 (software, Zeiss, Germany), randomized and then analysed blinded using Photoshop (Adobe, USA) and ImageJ (NIH, USA) including the CellCounter Plugin (NIH/University of Sheffield, UK). Cell density was assessed manually by counting six independent 0.1 × 0.1 mm-sized squares.

Statistics

Data are expressed as median ± 25%/75%-quantiles. Non-parametric Mann–Whitney U-test was used to compare ECL between groups over the cultivation time of 15 days using...
Results

In all three groups, the endothelial cell layer was preserved after 15 days of cultivation. However, analysis of the endothelial cell layer of the control group revealed a less irregular cell pattern (mostly hexagonal cells, only few destroyed (alizarin red stained) cells) compared to the phacoemulsification (polymorphic and enlarged cells, lower cell density and more destroyed (alizarin red stained) cells) and the irrigation group (more destroyed (alizarin red stained) cells) (see Figs 1 and 2). Both groups showed more obvious alizarin red areas (destroyed cells) than the control group (see Fig. 1).

The number of corneal endothelial cells (CECs) showed no significant difference between the control and irrigation group on day 1 (CONTROL: 4050 ± 175/267 cells/mm²; IRRIG: 4033 ± 233/67 cells/mm²; p = 0.710). Baseline ECD of the phacoemulsification group was significantly lower on day 1 compared to the control group (PHACO: 3767 ± 133/250 cells/mm²; p = 0.019). No significant differences were found between the irrigation and phacoemulsification group on day 1 (p = 0.240).

On day 15, we found a significantly lower ECD in the phacoemulsification group compared to both, the control (p < 0.001) and the irrigation group (p < 0.001) (PHACO: 2567 ± 317/267 cells/mm²; IRRIG 3450 ± 350/383 cells/mm²; CONTROL 3650 ± 288/258 cells/mm²; see Table 1 for data). No significant difference in ECD was

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Fig. 1. Photographs of the corneal endothelium on day 15 after staining with trypan blue and alizarin red S. The phacoemulsification group (PHACO, A) showed more destroyed areas than the control group (CONTROL, C) and endothelial cell loss was significantly higher than in the other groups. Also, the irrigation group (IRRIGATION, B) suffered obvious cell damage (alizarin red areas); however, endothelial cell loss was not significant compared to controls.

Fig. 2. Corneal endothelial cell density (ECD, endothelial cells per mm²). Baseline ECD on day 1 showed no significant differences between the control (CONTROL) and irrigation (IRRIG) group (p = 0.710). The phacoemulsification group (PHACO) showed a significantly lower ECD on day 1 compared to the control (p = 0.019) but not the irrigation group (p = 0.240). On day 15, the phacoemulsification group showed significantly less endothelial cells per mm² when compared to both, the irrigation group and the control group (CONTROL) (PHACO: 2567 ± 317/267 cells/mm² (median ± 25%/75%-quartiles); IRRIG: 3450 ± 350/383 cells/mm²; CONTROL: 3650 ± 288/258 cells/mm²; p < 0.001). The irrigation group did not differ significantly from controls on day 15 (p = 1.000). Box plot with whiskers representing minimum, Q25%, median, Q75% and maximum; *p < 0.05; **p < 0.001.
Table 1. Endothelial cell density on d1 and d15; absolute and percental endothelial cell loss within 15 days of cultivation

|          | ECD d1 (cells/mm²) | ECD d15 (cells/mm²) | Absolute cell loss (cells/mm²) | % cell loss |
|----------|--------------------|---------------------|-------------------------------|------------|
| Phaco    | 3767 ± 133/250     | 2567 ± 317/267      | 1233 ± 267/300                | 32.5 ± 7.0/6.4% |
| Irrigation | 4033 ± 233/67     | 3450 ± 350/383      | 450 ± 183/133                 | 11.8 ± 5.3/2.6% |
| Control  | 4050 ± 175/267     | 3650 ± 288/258      | 417 ± 138/179                 | 10.2 ± 3.2/4.6% |

Data shown as median ± 25%/75%-quartiles.

Fig. 3. Percental endothelial cell loss per mm² after 15 days of cultivation. The phacoemulsification group (PHACO) suffered a significantly higher cell loss compared to irrigation (IRRIG) and the control group (CONTROL) (see Table 1 for data; PHACO versus IRRIG: p < 0.001; PHACO versus CONTROL: p < 0.001). Box plot with whiskers representing minimum, Q25%, median, Q75% and maximum; * p < 0.01; ** p < 0.001.

observed between the irrigation and the control group on day 15 (p = 1.000) (Fig. 1). Also, the percental and absolute ECL within 15 days of cultivation was significantly lower in the irrigation (11.8 ± 5.3/2.6%; 450 ± 183/133 cells/mm²; p < 0.001) and control group (10.2 ± 3.2/4.6%; 417 ± 138/179 cells/mm²; p < 0.001) when compared to the phacoemulsification group (32.5 ± 7.0/6.4%; 1233 ± 267/300 cells/mm²) (Fig. 3).

Discussion

Phacoemulsification-related corneal endothelial cell (CEC) damage is a main concern of cataract surgeons. To our knowledge, a reliable and well-translatable ex vivo research model is missing so far, and most studies use animal experiments or clinical data to approach ECL caused by cataract surgery. This study combined a recently published porcine corneal endothelial research model, which shows a very constant endothelial cell decline during organo-typical cultivation for up to 15 days with the application of phacoemulsification ultrasound and/or irrigation and aspiration (I/A) prior to preparation and subsequent cultivation of split corneal buttons (Kunzmann et al. 2018).

Our results indicate that the presented model is sensitive to phacoemulsification damage. An ultrasound time (UST) of 5 min caused significant ECL compared to the irrigation and control group. Since irrigation itself did not alter ECL significantly, the additional ECL in the phaco group may confidently be attributed to phacoemulsification. As expected, due to a longer UST (30% phaco energy, total of 1700 J) exceeding the usual UST applied in patients, the ECL was higher than most clinical studies reported after phacoemulsification (6.5–6.9% within 3 months; 7.3–10.5% within first year (Bourne et al. 2004; Dick et al. 1996; Mencucci et al. 2006; Reuschel et al. 2010; Walkow et al. 2000)). Similar ECL rates (>30%) can be observed in high-density cataracts, where more energy is required (Gonen et al. 2012). Consequently, we consider our results correctly represent the damage caused by the applied amount of ultrasound energy. We established a phacoemulsification damage model with high ECL, because only with a substantial ECL, possible rescue effects of protective interventions may be observed. This is not possible with a much shorter UST (no significant changes in ECL at 15-day follow-up due to standard deviation etc.) or longer UST (uneven/patchy endothelial damage disallowing ECD analysis; unpublished data). We think that low ECL rates in most studies could be the reason for nonsignificant results in many clinical studies (Praveen et al. 2009; Vasavada et al. 2010; Kugu et al. 2015; Taskin & Aslan 2018).

Another recently published ex vivo model also used whole porcine eyes and trypan blue and alizarin red staining to assess endothelial cell damage after the application of ultrasound energy (Rouhbakhshzaeri et al. 2018). However, several aspects with a decisive negative impact on the results were disregarded. There is no precise information on the size of the analysed endothelial area and the phaco tip’s exact position during phacoemulsification (i.e. pupil’s centre or off-centre) (Rouhbakhshzaeri et al. 2018). Moreover, staining and examination of the CEC was performed after only 4 hr of incubation, which is only useful to assess necrotic cell death. However, this completely neglects apoptotic cell death processes (Rouhbakhshzaeri et al. 2018). In our model, CECs were allowed to reorganize and cover damaged areas – comparable to the in vivo situation – over a period of 15 days.
Thus, corresponding cell damage is rather seen in cell enlargement but not trypan blue stained areas. Although major ECL is seen directly after phacoemulsification, increased ECL occurs for many years following cataract surgery (Bourne et al. 1994, 1997). Also, ultrasound energy was applied in bevel-up position (phaco tip opening facing CECs) in the study by Rouhbakhshzeraei et al. (2018). We used the bevel-down orientation, which in our opinion — represented in a coherent endothelial cell layer — could result in a more homogenous energy distribution towards the endothelium, whereas bevel-up orientation, emitting energy directly towards the endothelium, is more likely to cause uneven and rather localized ECL (Raskin et al. 2010; Rouhbakhshzeraei et al. 2018). Current literature is not completely congruent on this aspect and ongoing investigations are further addressing this issue (Frohn et al. 2002; Coelho et al. 2005; Raskin et al. 2010; Faramarzi et al. 2011; Kaup et al. 2016).

Furthermore, the correct anatomical structures and proportions are essential for a reliable ex vivo model to correctly respect fluidics and energy distribution during phacoemulsification. Complex fluid turbulences within the anterior eye chamber caused by I/A were identified to potentially damage CECs, whereas other studies negotiate negative alterations of hydrodynamic parameters on postoperative ECD (Hayashi et al. 1996; Baradaran-Rafii et al. 2009). Turbulences in vivo during I/A procedures can be quite complex as different surgical approaches and I/A systems cause different turbulence patterns (Abouali et al. 2011). Hydrodynamic laws have been applied to explain that a concentric reverse flow is enabled when the irrigation solution reaches the peripheral cornea, where it then may possibly cause cell damage (Ghaifariyeh 2010). While our results revealed no significantly higher ECL in the irrigation group compared to controls, there were more alizarin red, thus destroyed cells in the irrigation group, which is similar to the diffuse endothelial cell damage described after irrigation without causing significant ECL in other studies (Edelhauser 1975; Binder et al. 1976).

In general, in vitro cell cultures are the first choice in screening experiments. However, CEC cultures do not behave like CECs in vivo because they undergo endothelial-mesenchymal transition (EMT) resulting in fibroblast-like morphology and properties as well as in the loss of endothelial cell polarization (Roy et al. 2015). Results from clinical studies and animal experiments often offer highly predictive results but are usually very resource- and time-consuming and normally restricted to a special subject of interest, also due to ethical reasons. Testing of multiple settings (i.e. various levels of ultrasound energy) would require numerous patients or animals. Here, pig eyes seem to be the only adequate substitutes due to similar size and properties (Van Horn et al. 1977).

Conclusively, the proposed ex vivo phacoemulsification model enables future investigations of the effects of various phacoemulsification regimens, phacoemulsification energy and ultrasound parameters in bevel-up position during irrigation/aspiration in cataract surgery in order to minimize ECL at low cost and to decrease the number of animal experiments.

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All parts of the presented experimental study were performed in accordance with the ethical tenets of the Declaration of Helsinki.