Medical Devices: Evidence and Research

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ORIGINAL RESEARCH

Discrepancies in CDE and Measured Phaco Tip Energy: Comparison of Energy Produced in Longitudinal and Torsional Ultrasound Using Calorimetry

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Purpose: This study aims to investigate the differences between the heat energy produced during cataract surgery and Cumulative dissipated energy (CDE). CDE is often used as a medium for understanding the energy delivered to the eye during cataract surgery. However, the actual energy produced at the tip level of the tip is not well understood. We propose that a discrepancy may exist between the CDE reported by the surgical machine and the actual energy delivered to the eye.

Methods: About 50 mL of distilled water were degassed and placed in an isobaric calorimeter. Using the Alcon Centurion and Ozil handpiece fitted with the balanced tip, an investigator immersed the phaco tip into the water and pressed the foot pedal to position 3. The device was set to 100% continuous power, vacuum to 0 mmHg, with aspiration 12 mL/min aspiration. To prevent system changes in the system within the calorimeter, the aspiration tubing was occluded. Temperature change recorded by another investigator was observed from 0 to 60 seconds. After 60 seconds the first researcher immediately released the pedal and removed the phaco tip from the water. Trials were performed 10 times using solely torsional or longitudinal settings and averaged. CDE also was recorded and averaged.

Results: No significant difference was seen in the temperature change or energy calculated in Joules between ultrasound modalities, with torsional producing a magnitude of 163 J and longitudinal producing 172 J ($P = 0.2$). However, the CDE generated in the 60 seconds period was significantly different, with a magnitude of 61 for longitudinal compared to 24 for torsional ($P < 0.001$).

Conclusion: Significantly more energy was generated using torsional ultrasound than longitudinal at the tip level of the tip. CDE did not appear to accurately reflect these differences. This suggests that other factors should be considered when evaluating CDE and surgical outcomes.

Plain Language Summary: This study looked at possible differences between the energy generated during cataract surgery that is reported by the surgical device and the actual energy measured as thermal heat using different machine settings, namely longitudinal and torsional ultrasound. A common metric used for energy delivery to the eye is cumulative dissipated energy. The problem is that this measure accounts for the energy delivered to the eye where the surgical instrument passes through the cornea. Energy that is produced by the rest of the instrument that is inside the eye is less understood, although others have studied postoperative outcomes. We used a method called calorimetry to measure the thermal heat produced by the entire tip and compared this to what the machine reported as cumulative dissipated energy. Calorimetry calculates energy by measuring the change in temperature of liquids. The surgical instrument generated heat in a chamber containing water, and we used the change in temperature to calculate the energy produced by the surgical instrument. We found that longitudinal and torsional ultrasound produced similar heat energy, but the machine reported very different energy. Our results suggest that the machine may not be reporting all of the energy which the surgical instrument produces, and that surgeons may not be able to rely on cumulative dissipated energy to predict operative outcomes.

Keywords: Cumulative dissipated energy, phacoemulsification, calorimetry, torsional ultrasound, longitudinal ultrasound

Received: 3 August 2024
Accepted: 4 October 2024
Published: 17 October 2024

Introduction

Phacoemulsification (phaco) utilizes ultrasound (US) energy to break up cataracts. Studies have shown that energy released in excess by ultrasonic waves can cause damage to structures in the anterior chamber.[1] Though phaco is one of the most commonly performed surgical procedures in the United States, there is insufficient data on total thermal energy delivered during a standard procedure.[2]

In general, US produced during phaco is a conversion of electrical energy into ultrasonic vibrations that are utilized for cutting and breaking apart lens tissue. The US waves are generated by an electric current that causes vibration of a piezoelectric material within the handpiece.[3] The frequency at which these vibrations occur is so high (<20 khz) that it is inaudible and so the term ultrasound is used. The idea of using US for phaco was discovered by Charles Kelman after a visit to his dentist.[4] Similar to dental instruments that use US to apply energy to tissue, phaco devices use US as the modality for lens fragmentation during cataract surgery.

Currently, there is great interest in producing machines that can generate phaco energy with various US modalities, as well as in the study of how these modalities impact outcomes.[5,6] These include the use of longitudinal US, torsional US, or some modification of both. The mechanical properties of longitudinal and torsional US differ in the way that the tip oscillates. In longitudinal US, the tip oscillates in a forward and backward motion at a constant frequency. As power is increased, the stroke length of the tip is lengthened. This results in increased tip oscillation amplitude, which increases energy delivery and power for lens fragmentation. Alternatively, torsional ultrasound oscillates laterally, from side to side. As power is increased, the amplitude also becomes greater; this generates increased cutting power at the tip. The mechanisms by which these modalities function have also been analyzed in prior studies.[7]

There are several components of phaco that comprise the total energy delivery into the eye during surgery. These include heat energy produced by the piezoelectric material and the phaco tip shaft that is moving within the sleeve, as well as energy produced by oscillation of the phaco tip as the US waves are conducted into the tip material. Other factors include fluid movement, lens particle turbulence and chatter, and cavitation. The cumulative effect of these different factors constitutes the total energy delivered to anterior segment tissue during a cataract surgery procedure.

In order to quantify and predict total energy delivery to the eye, some companies have developed means by which to calculate total energy based on machine settings and the total elapsed time of actual phaco. An example is cumulative dissipated energy (CDE), which is a number generated by phaco machines that are designed by Alcon.[8] CDE is a measure in joules (J) of the energy produced by the tip at the level of the wound. That is to say, it is a measurement of energy produced by friction of the tip against the cornea in the wound tunnel. Currently, CDE is defined as the total US energy generated in foot pedal position 3. This is calculated in Equation 1.

$$(\text{Longitudinal Time x Average Longitudinal Power}) + (\text{Torsional Time x 0.4 x Average Torsional Amplitude}) \quad (1)$$

The factor 0.4 represents the approximate reduction of the heat dissipated at the incision compared to the longitudinal phaco. Though CDE helps surgeons estimate the amount of energy production at the level of the wound, it is less understood if any variation exists in energy production along the tip shaft and at the distal end of the tip.

It is important for surgeons to understand the kinetics of cataract surgery both at the wound and distal tip due to possible complications that can occur in those locations. For example, excess heat produced by the phaco tip in the wound tunnel can result in wound burn which causes permanent corneal damage requiring transplant. With respect to the distal tip, the energy used to break up lens tissue also has the potential to damage other intraocular structures including the corneal endothelium and posterior capsule. For this reason, surgeons use CDE as a way to gauge how much energy is delivered into the eye, although it only describes energy delivery at the wound and may not reflect distal tip energy production.

Previous studies have evaluated differences between torsional and longitudinal US with respect to efficiency and corneal endothelial cell loss.[9–11] However, to our knowledge no study has quantified the energy using isobaric calorimetry as a means to quantify total intraocular energy, as many studies rely on CDE as the standard for energy delivered to the eye.[12–14] This study aims to compare total energy production with a calorimetry model against the traditional CDE model for understanding total energy delivery during phaco.

Previous work has shown calorimetry to be an accurate model to determine ultrasonic power.[15] In this study, we proposed that phaco energy produced at the phaco tip could be captured and quantified using calorimetry. We also felt that different amounts of energy might be produced by torsional and longitudinal US during a set time period, with these differences not accurately accounted for by the reported CDE as CDE calculates energy delivery at the wound without consideration of the distal shaft and tip.

Materials and Methods

Since this study did not involve human subjects, Institutional Review Board approval was not required.

Materials

The phaco surgical platforms used were the Alcon Centurion with the Ozil handpiece (Alcon, Fort Worth, Texas, USA) and balanced tip.

Methods

Calorimeter Calibration

Distilled water was degassed to avoid acoustic cavitations interfering with results. Degassing involved bringing distilled water to a boil, placing the liquid in a sealed container, and placing it in the refrigerator to bring the temperature back down. The water was used as soon as the temperature of the water returned to room temperature (approximately 20 degrees Celsius). The calorimeter was first calibrated with an electric DC power supply. The power supply was set at constant 9V and 3.00A (27W), and 100mL of distilled water was heated for 1 minute in the calorimeter chamber. Temperature change was measured over duration and the energy (E) was calculated by the equation $E = VIt$. The calibration factor (cf) was calculated using the equation $cf = E/\Delta C°$.

Experimental Design

This study was based on the first law of thermodynamics, which states that energy cannot be created or destroyed, but only can be converted from one form to another.[16–18]

$$\Delta U = q + w \tag{2}$$

Change in temperature of water of a known mass and specific heat capacity can be used to calculate the total energy produced along the tip shaft and at the phaco tip. Thus, Equation 1 can be rewritten as Equation 3:

$$q = mc\Delta T \tag{3}$$

Mass of the water (m), specific heat (c), and observed temperature change (ΔT) were used to calculate the total energy produced along the shaft and at the tip.

Approximately 50 mL of degassed distilled water was weighed on a scale and mass was recorded. Water was placed in the inner chamber of the calorimeter and the lid was put in place. An investigator immersed the phaco tip to the shoulder of the tip sleeve into the water contained within the calorimeter, and this investigator operated each phaco surgical platform by pressing the foot pedal to position 3. Settings were as follows and were conserved with the exception of US setting: 100% torsional or longitudinal power, flow rate 12 mL/min, vacuum 0 mmHg, continuous US.

To prevent changes in the system within the calorimeter, the aspiration tubing was removed from the handpiece and occluded with a hemostat (Figure 1). Changes in temperature were observed from time 0 to time 60 seconds, and recorded by a second investigator at times 0, 15, 45, and 60 seconds (Figure 2). Trials were performed 10 times using each setting and averaged. After each trial, the water within the calorimeter chamber was replaced to account for any potential loss of small amounts of fluid. The phaco handpiece was also allowed to cool between trials by placing in room temperature water for 1 minute. CDE recorded by the machine also was recorded and averaged for each trial.

It was felt that a longer duration of phaco would be required in order to measure a significant change in water temperature which is why a 60 second trial was chosen. Flow rate was placed to 12 mL/min because this was found to be the lowest flow rate setting on the phaco machine. And to ensure the water mass did not change within the calorimeter

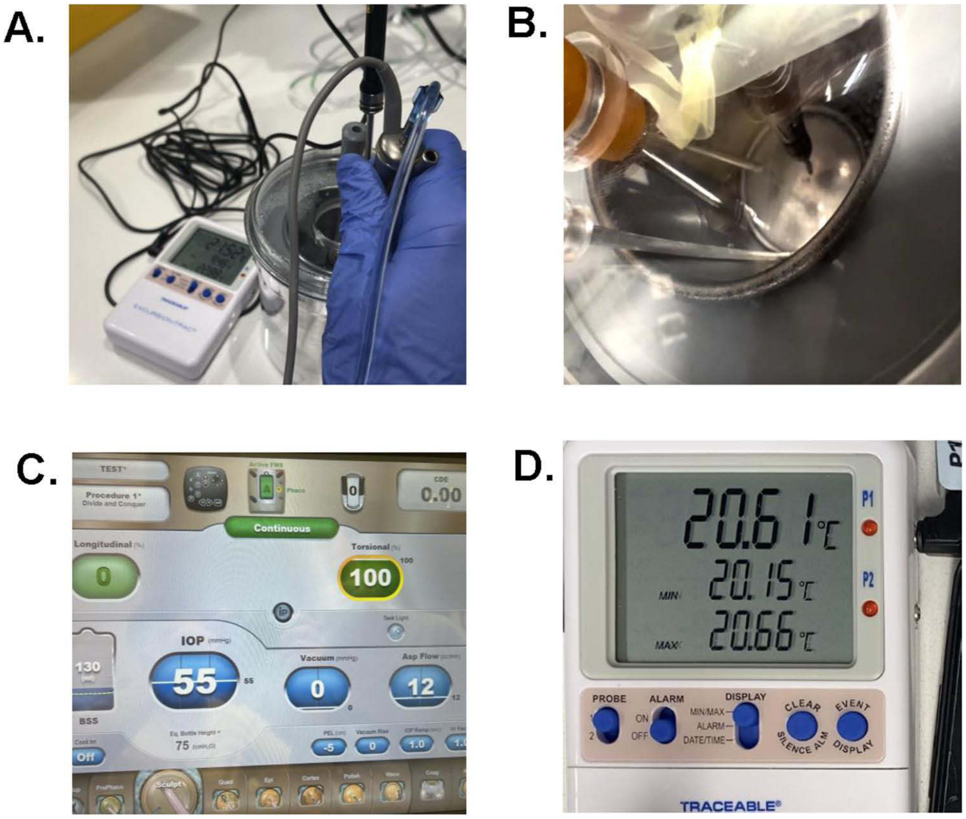

Figure 1 An Isobaric calorimeter was used for measuring phaco tip energy. The handpiece was inserted into the chamber (**A**) with inflow and outflow tubing occluded. The tip was submerged in the water (**B**) and the foot pedal was pressed to position 3 for 60 seconds at 100% power (**C**). Change in temperature was measured **(D)**.

chamber, the outflow tubing had to be manually occluded with a hemostat to prevent fluid aspiration. During trials, the machine alerted us to an occluded state which confirmed total occlusion during experimental trials. And although 50 mL of water is a significantly larger volume than what is contained in the anterior chamber, it was necessary to use this volume so that the phaco tip could be lowered into the calorimeter chamber without contacting the calorimeter base.

Statistical Methods

Microsoft Excel (version 16.60) was used for data tracking and compilation, and for statistical analysis.

Thermal energy emitted by the US waves was calculated using the calorimetry equation $Q = mc\Delta T$, using distilled water with a specific heat capacity of 4.184 J/gK. An assumption was made that all trials, regardless of starting temperature, contained distilled water with this specific heat capacity as mild changes in temperature have negligible effect on specific heat capacity. It was expected that not all US energy would be absorbed into thermal energy during phaco; a conversion ratio could then be identified.

For each change in temperature measured during phaco, ten replicate trials were averaged, and the standard deviation was found. 10 recorded CDE measurements also were averaged, and the standard deviation was recorded. A Student's *t*-test was performed to deduce which groups were significantly different ($P < 0.05$).

Results

After careful measurement by calorimetry with the methodology described above, we found torsional and longitudinal US produced similar total energy in a 60s time period with torsional producing an average magnitude of 163.02 J and longitudinal producing an average of 172.45 J but these differences were not significant ($P = 0.2$) (Figure 3). However, CDE accumulated at significantly different rates when comparing the two settings, with approximately twice as much CDE for longitudinal US compared to torsional with magnitudes of 60.6 and 24.0 respectively ($P < 0.001$). The energy

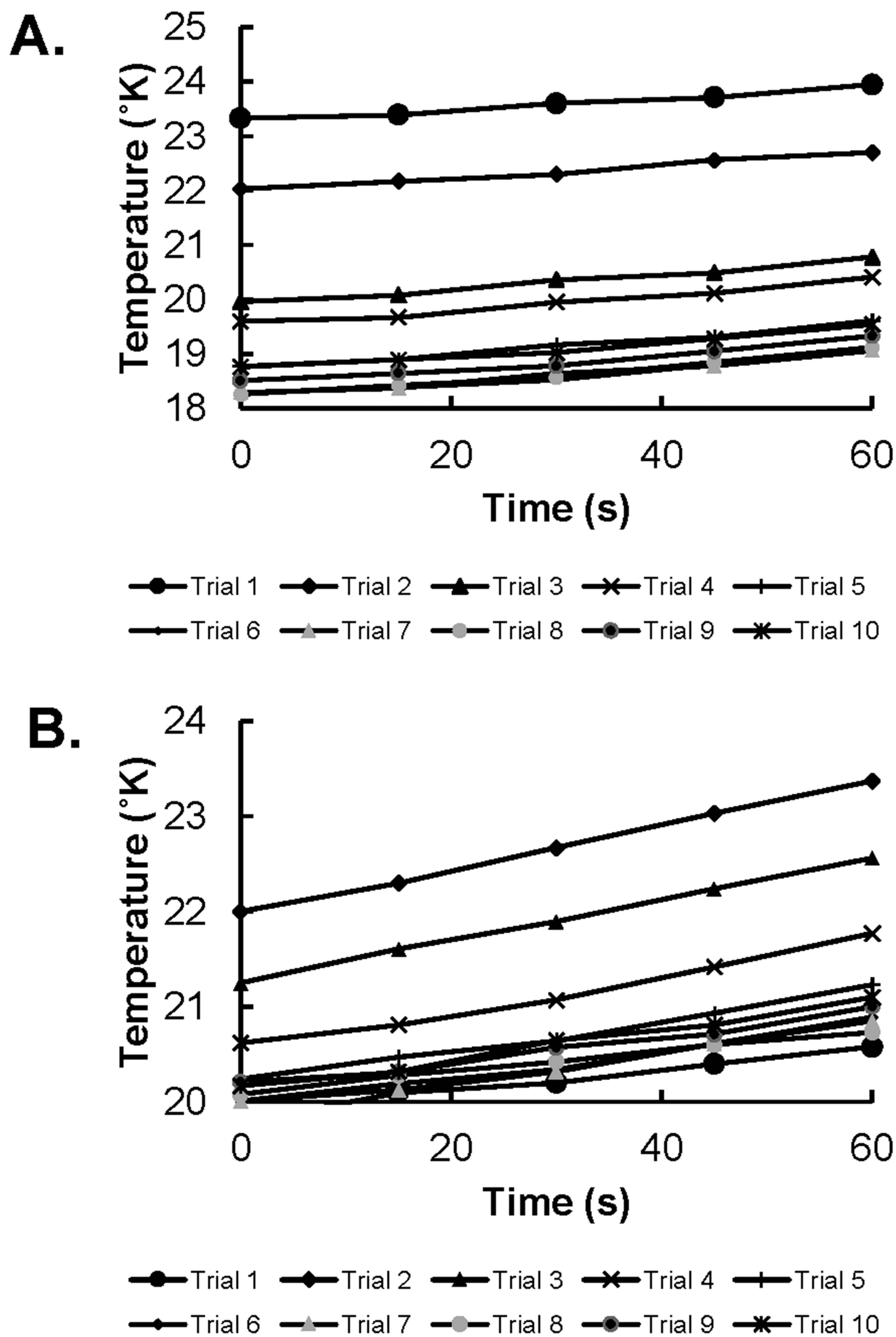

Figure 2 The rise in temperature over time of distilled water contained within an isobaric calorimeter. Ultrasound energy was generated by the Alcon Centurion with 100% torsional (**A**) and longitudinal (**B**) power settings.

that was generated per CDE unit in torsional and longitudinal US was significantly different, with approximately twice as much energy generated by torsional US at the level of the tip per CDE unit compared to longitudinal (Figure 4).

The investigators also found that after 5 or more repeat trials, that the phaco tip became loose. This resulted in some variability in temperature change in both torsional and longitudinal settings. These errors were consistently noted by the

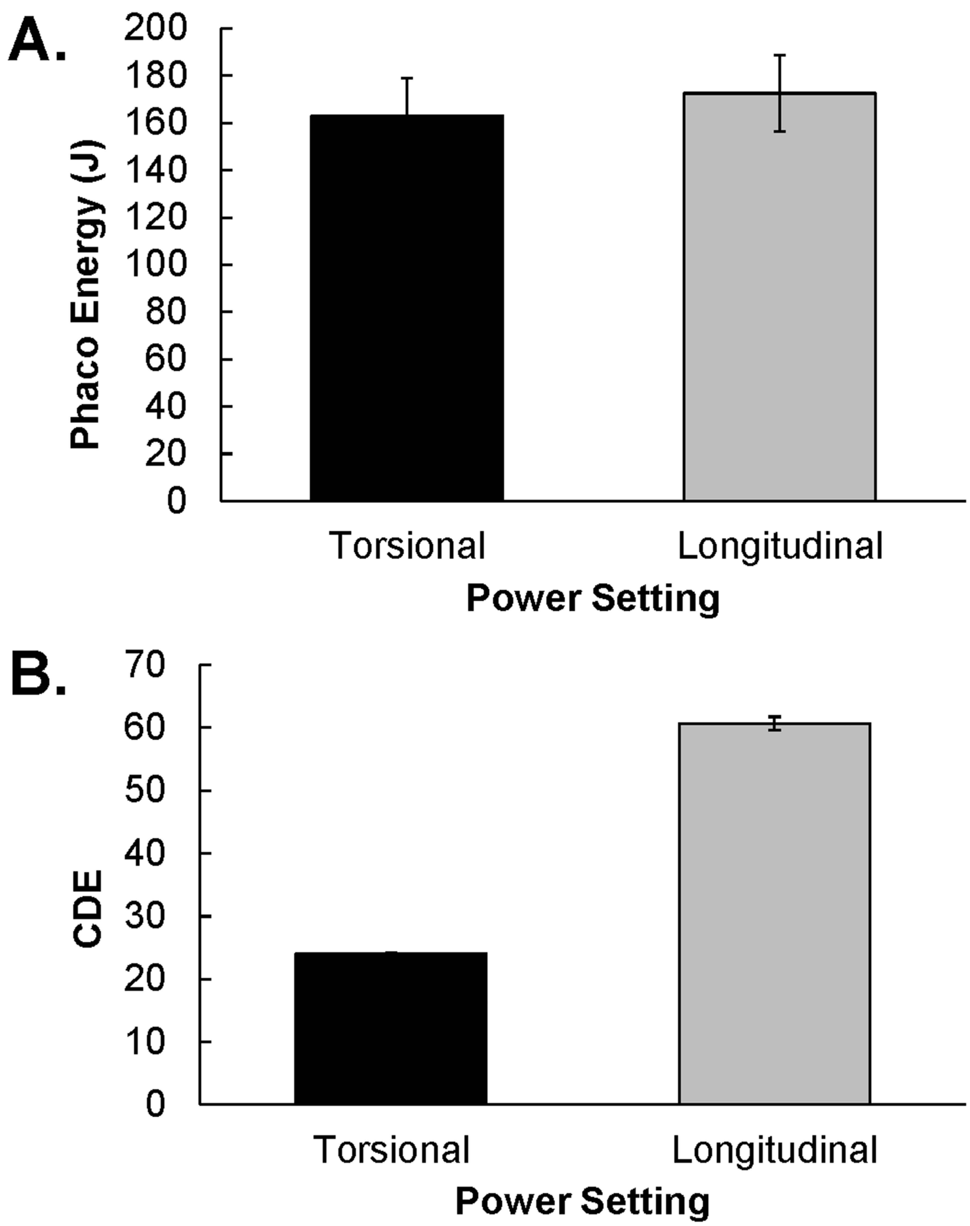

Figure 3 Average phaco tip energy generated by the Alcon Centurion with torsional and longitudinal ultrasound (**A**) and associated CDE reported by machine interface (**B**). Energy was calculated using the calorimetry equation and change in temperature of distilled water within the calorimeter chamber. Trials were repeated 10 times for each US setting. Differences in tip energy production between settings were not statistically significant ($P = 0.2$) but differences between generated CDE in a 60 second time period were statistically significant ($P < 0.001$).

investigators after several repeat trials. To mitigate the error, the tip was tightened after every 5 trials to ensure consistent results. Trials where the tip was found to be loose were not included in the final data interpretation.

Discussion

Understanding total energy delivery to the eye is important for surgeons in order to mitigate complications during cataract surgery and to optimize efficiency.[19,20] However, the quantity of total energy production that incorporates the distal shaft and phaco tip has been unclear among phaco machines and no standardization of power units has been developed, causing possible differences among machine manufacturers. Furthermore, comprehensive total energy differences that result from changes in ultrasound settings, such as switching from longitudinal to torsional, may not be fully accounted for by established energy estimation modalities. This has been due to a lack of methodology for phaco

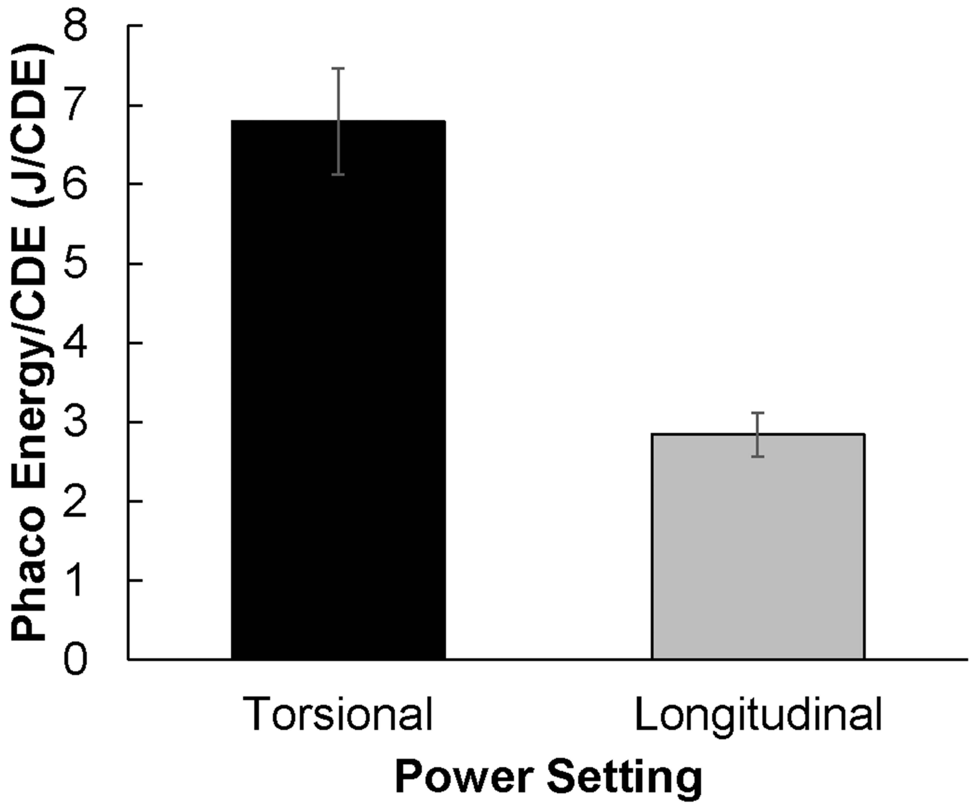

Figure 4 Measured phaco tip energy of longitudinal and torsional ultrasound that are normalized with the CDE reported by the machine interface. Differences among normalized values are statistically significant (P < 0.001).

tip energy measurement that has the ability to account for all complex variables other than energy delivery at the wound. For this investigation, we developed a novel methodology using calorimetry in order to measure the total energy produced not only at the wound but also along the entire phaco shaft and distal phaco tip (Figure 1).

The novel methodology proposed in this study appeared to capture energy produced by a phaco handpiece under an occluded state. A 60 second duration was sufficient time to measure a significant difference in water temperature, even at the volume required in this study. The phaco handpiece was able to operate under conditions of total occlusion, and repeat trials showed consistent results with minimal variation. Initially, it was found that the phaco tip became loose after 5 or more repeated trials. The machine notified us of this error and this was promptly addressed by tightening the tip after every 5 trials; this allowed for consistent data acquisition.

We recognize that previous studies have shown differences in surgical outcomes when comparing torsional and longitudinal ultrasound settings.[21–23] One recent example of these differences includes the determination of significant differences in longitudinal and torsional US when evaluating endothelial cell damage.[24] Other studies have shown differences in cavitation between longitudinal and torsional ultrasound with longitudinal having a greater propensity for generating cavitation at lower power levels.[25] However, in our study we showed that differences in total energy delivery at the level of the tip were not statistically different between torsional and longitudinal US in an occluded state. This does not account for nonoccluded scenarios where the fluid is continuously being infused and aspirated from the anterior segment. Regardless of occlusion, CDE accumulated at a significantly higher rate in longitudinal US when compared to torsional (Figure 3).

The relationship between tip movement and movement of the tip shaft that is located in the wound tunnel differs between longitudinal and torsional ultrasound. When using longitudinal settings, the phaco tip moves forward and backward in a jackhammer-like manner. The distal tip travels the same distance as the shaft which is located in the wound tunnel. Friction is generated at the level of the wound as the tip moves forward and backward within the sleeve;

this friction subsequently transmits energy into the cornea. The mechanics of torsional US differ significantly. While working under torsional settings, the oscillation is occurring in a side-to-side motion rather than forward to backward. At the level of the tip, the amplitude traveled is greater than the amplitude traveled more proximal along the tip shaft. Therefore, when using torsional US, the energy produced at the level of the tip is greater than the energy produced at the level of the wound. This difference explains why CDE accumulation is significantly smaller for torsional when compared to longitudinal, even when phaco tip energy production is not statistically different between the two modes. This also means that less friction is produced at the level of the wound when using torsional US when compared to longitudinal, which explains why they can produce similar energy at the level of the tip but have different outcomes with respect to corneal endothelial cell damage.

These results suggest a new way of approaching interpretation of surgical outcomes in relation to reported CDE. CDE may remain an appropriate representation of the energy dissipated in the wound tunnel, but with respect to the energy generated at the level of the tip, the interpretation should consider US settings. Understanding the limitations CDE presents with respect to energy production is clinically relevant because as surgeons use torsional or longitudinal settings for different cases, they might erroneously assume that since CDE accumulates at a lower rate in torsional US that there is less energy produced at the distal tip. However, our studies show that more energy is delivered at the tip per CDE unit in torsional US which supports using lower power settings in torsional US to protect intraocular structures.

The discrepancy in reported CDE and calculated phaco tip energy reveals that machine settings may not be adequately accounted for in CDE reporting. When the machine is placed into torsional setting, CDE accumulates at a specific rate, depending on power setting and duration of the foot pedal in position 3. When the machine is placed into a longitudinal setting, CDE accumulates at a different rate as established by the manufacturer. This is likely because at the level of the wound, different amounts of friction are generated depending on which US setting the surgeon is using. Understanding how energy delivery at the wound alone compares among US modalities is an important consideration for surgeons and our lab has commenced conducting studies to explore this further.

Since quantifying phaco energy delivery to the eye is essential for improvement of patient outcomes in cataract surgery, future directions of this work include exploration of differences in thermal energy output between settings, tips, handpieces, and machines. It is reasonable to assume that phacoemulsification with less thermal energy release has lower potential to damage the corneal endothelium, thus identifying which phacoemulsification settings release the lowest amount of thermal energy in a quantifiable manner.

We acknowledge that evaluating phaco tip energy with calorimetry does present limitations in the scope at which this data can be generalized to clinical scenarios. With our methods the phaco tip had to be operated under complete occlusion for an extended period of time which would not occur clinically. In order to accomplish this, vacuum had to be set to 0; and because the aspiration flow rate could only be set to 12 mL/min, the tubing had to be occluded with a hemostat. Under regular operating conditions, the phaco handpiece would not be subjected to complete occlusion in this manner. However, it was necessary to operate the handpiece in this fashion in order to use the calorimetry equation to calculate the energy generated at the tip. That is to say, there could be no change in water mass for the duration of energy transfer into the system. Under occlusion by the hemostat, we created a physical occlusion, and the machine notified us of the occluded state for the duration of the experiment. Our calorimeter chamber also contained 50 mL of distilled water–a volume that far exceeds that of the anterior chamber. This was necessary to allow for the phaco tip to be immersed in the calorimeter chamber without the phaco tip coming in contact with the calorimeter itself. Even though the volume was high, it should be noted that the calorimeter equation normalizes the energy for water mass. We also recognize that operating the phaco handpiece for 60 seconds in an occluded state is not performed clinically. It was felt that a total of 60 seconds was required in order to measure a significant change in the temperature of the water.

Further limitations of our calorimetry model are that it does not differentiate between the different components of energy that add up to total energy delivery to the eye. All forms of energy were assumed to be transferred to heat; however, in an occluded state we recognize that the heat produced from the piezoelectric material and the sleeve may exceed the heat produced by oscillation of the phaco tip with different settings. Additionally, we are unsure how well we are capturing heat generated from cavitation as we are using an isobaric calorimeter which is open to the atmosphere.

This study is also limited to the Alcon Centurion surgical platform. These results may not reflect differences between torsional and longitudinal US in other devices with various other phaco tips. There may also be differences at different power levels and settings such as pulse and burst, etc. Further studies that could measure phaco energy production at the level of the tip in vitro would be valuable.

In conclusion, machine settings such as US settings should be considered when using CDE as a representation for total energy delivery to the eye. When using the Alcon Centurion device reported CDE likely helps surgeons understand how much energy is delivered to the wound tunnel and surrounding cornea, but it is less effective at helping surgeons understand energy delivery along the distal shaft and tip. We showed this relationship by measurement of phaco tip energy using isobaric calorimetry which proved to be an effective method for repeatable and consistent data acquisition. When switching between longitudinal and torsional mode, surgeons may want to use lower power settings in torsional mode to avoid excess energy distribution from the phaco tip to protect intraocular structures.

Acknowledgment

Susan Schulman assisted with editing and manuscript preparation.

Funding

This study was supported in part by a grant from Research to Prevent Blindness, Inc., New York, New York, USA. The sponsor had no involvement in any of the stages from study design to submission of the paper for publication.

Disclosure

Dr. Olson is on the Board of Directors of Perceive Bio and the Scientific Advisory Board of Perfect Lens. Dr. Pettey reports consulting for Zeiss and Alcon during the conduct of this study and consulting agreement for Lensar, outside the submitted work. The authors report no other conflicts of interest in this work.

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