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ORIGINAL RESEARCH

Comparison of Ultrasound Energy Delivered to the Anterior Segment Across Different Phacoemulsification Surgical Platforms

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Purpose: The aim of this study was to use calorimetry to understand the difference in energy transferred by three phacoemulsification surgical platforms to the eye.

Patients and Methods: A phacoemulsification tip was lowered into a double-walled calorimeter filled with distilled water. The foot pedal was depressed for 30 seconds and the change in temperature of the water was measured by a temperature probe. Three phacoemulsification systems were compared: the Alcon Centurion, Johnson & Johnson Veritas and Oertli CataRhex 3. The following conditions remained constant across trials and platforms: continuous longitudinal ultrasound, flow rate 12mL/min, vacuum 0mmHg, and clamped inflow and outflow tubing. The different platforms were directly compared at 20%, 40%, 60%, 80% and 100% power.

Results: A two-way ANOVA found a significant difference ($P < 0.001$) in overall energy output across all trials between the CataRhex 3, Centurion and Veritas with an F value of 63.97 and two degrees of freedom.

Conclusion: Given identical settings, the amount of energy produced was significantly different across phacoemulsification platforms. This data can aid surgeons' understanding of how power level by surgical platform can impact the amount of energy introduced into the anterior segment during cataract surgery.

Plain Language Summary: Cataract surgery is one of the most commonly performed surgical procedures in the United States. The most common surgical technique used to remove cataracts is called phacoemulsification (phaco), which utilizes ultrasound energy to break up and remove cataracts.

Utilizing phaco to emulsify cataracts is safe and effective; however, because of the delicate nature of the structures in the eye, the amount of ultrasound energy delivered during the surgery is an important consideration to avoid adverse outcomes.

There are a variety of phaco platforms (machines) used for cataract surgery. While it is beneficial for surgeons to have many options of surgical platforms, proprietary engineering makes it difficult to know how these surgical platforms compare to one another, especially in important variables such as energy delivery to the eye. To date, it has been unknown how the amount of energy delivered by these phaco platforms differs, if at all, when using identical settings during surgery. We did this study to find out if there are energy differences.

To do this research, our lab used calorimetry, which is a way of measuring energy transfer, to compare three different surgical platforms at the same settings. We found a statistically significant difference in amount of energy between these surgical platforms.

These results are important because they may help surgeons to understand that the amount of energy delivered during cataract surgery will be different depending on which surgical platform they are using and help to prevent adverse outcomes caused by delivering too much energy to the eye.

Keywords: calorimetry, cataract, surgery, complications

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Introduction

Phacoemulsification (phaco) is a form of cataract surgery that uses ultrasound energy to break up and remove cataractous crystalline lenses. The removal of the cataractous lens occurs in the anterior chamber space, with an average volume of 220 microliters, and in the capsular bag, which is approximately twenty microns in thickness. [1] The lens is surrounded by the iris and the endothelium, both of which are delicate structures. [2] While phaco for cataracts is safe and effective, it is not without the possibility of serious complications given the use of high-energy ultrasound, including posterior capsular rent,[3] wound burn[4,5] and corneal endothelial cell damage,[6,7] among others. Given the intricate and delicate nature of the surrounding structures and the risk for complications, it is critical to understand the amount of energy delivery introduced into the eye during cataract surgery. To date, the magnitude of energy delivered to the anterior segmented has not been discretely quantified, or evaluated across platforms. There are reported metrics of energy such as cumulative dissipated energy (CDE) and effective phaco time (EPT).[8–11] These metrics are a formulaic reporting of energy during ultrasound delivery,[9] but how CDE and EPT compare to each other, or how much energy is actually delivered to the eyes are unknown. Understanding how these metrics compare to the actual energy delivered to the eye improves surgeons' understandings and can allow for improved surgical outcomes.

During phaco, piezoelectric crystals respond to an electrical impulse which is converted to mechanical energy that causes the phaco tip to rapidly oscillate back and forth, creating the so-called "jackhammer" effect, and which is used to physically break up cataracts during surgery. Another phenomenon that produces energy is that of cavitation, which occurs during phaco when the rapid back and forth movements rapidly create micro bubbles with subsequent implosion and acute energy release to the tissues.[12] Together, these mechanisms, as well as any energy produced through fluid dynamics, add up to represent the total amount of energy produced during phaco.[6]

Calorimetry is the process of measuring the amount of energy produced by a chemical or mechanical process.[13] It is based in the first law of thermodynamics and the law of conservation of energy, which simply states that energy cannot be created nor destroyed, it can only change forms.[14,15] Calorimetry is performed using a calorimeter, which is an insulated vessel used to prevent heat loss from the experimental system. The calorimeter is filled with a liquid with a known specific heat capacity, which is a constant, and which allows the experimenter to know how much energy was introduced to the insulated system by measuring the change in temperature of the liquid. Thus, by measuring the change in temperature within the calorimeter, the amount of energy delivered into the system can be calculated.[13,16]

There are many phacoemulsification platforms, with a variety of power modulation settings from directionality of ultrasound, to the temporal pattern of energy delivery. The power magnitude setting across machines is titratable from zero to 100%, which allows surgeons to fine-tune the power delivered to the handpiece,[17,18] and theoretically by extension, to the eye. Because each platform is independently designed and produced, no standard exists for how much energy is produced at a given power level. Therefore, it remains unknown how the amount of energy produced varies from platform to platform.

Our purpose is twofold: first, we intend to understand how the amount of energy delivered to the anterior segment of the eye varies at different power levels within the same surgical platform. In addition, we aim to elucidate how the amount of energy produced varies across surgical platforms at a given power level.

Materials and Methods

This study did not involve human subjects or animals, so Institutional Review Board approval was not required.

Calorimetry

A double-walled calorimeter was filled with 50 mL of distilled water. A temperature probe was inserted through the dedicated opening in the lid. A handpiece tip was lowered through the center opening in the lid. A small ring mixer was used to gently agitate the water to evenly distribute heat throughout the entire volume (Figure 1).

In order to correctly measure the amount of energy produced with phaco, a constant, known volume of distilled water was required throughout each trial. To minimize the addition of balanced salt solution (BSS) or removal of distilled

Figure 1 (**A, B**) Photographs of the experiment setup for each trial including the calorimeter, temperature probe and monitor, phacoemulsification handpiece and ring mixer. Also shown in Panel B are metal clamps on the inflow and outflow tubing.

water, the vacuum and aspiration were set to their lowest possible settings, 0mmHg and 12mL/min, respectively. More importantly, metal clamps were placed on both the inflow and outflow tubing to prevent flow.

The amount of energy produced by phaco was calculated using the equation:

$$Q = mc(T2 - T1)$$

where Q is the amount of energy produced in joules (J), c is the specific heat capacity in J per gram times degrees Celsius (J/g°C), and T2 and T1 represent the final and initial temperature in °C. The specific heat capacity is a constant that is a property of the liquid used; in our experiments we used distilled water with a specific heat capacity of 4.184 J/g°C.

Phaco Platforms

The Alcon Centurion (Alcon Inc., Fort Worth, Texas, US), Johnson & Johnson Veritas (Johnson & Johnson Vision, Santa Ana, California, USA), and Oertli CataRhex 3 (Oertli Instrumente AG, Berneck, Switzerland) phaco platforms were used. The Centurion was fitted with the Ozil handpiece, the Veritas with the Whitestar handpiece, and the CataRhex 3 with the Titano Hexadisq handpiece. Each was fitted with their standard tip and set up according to their specifications prior to beginning the trials.

Trials

An empty graduated cylinder was weighed on a scientific scale and the tare button was pressed. 50 mL of distilled water was measured, and the weight of the water was recorded. The water was then placed in the double-walled calorimeter, which was fit with a small ring mixer and temperature probe. The handpiece was lowered into the distilled water and the initial temperature was recorded. Then, the foot pedal was depressed for 30 seconds to activate the ultrasound in the distilled water. The change in temperature of the water was measured by a temperature probe until the maximum temperature was reached. The starting temperature was subtracted from the max temperature to calculate the temperature change.

All trials were carried out using continuous longitudinal ultrasound. We performed 5 replicate trials at each of the following power levels: 20%, 40%, 60%, 80% and 100%.

Statistical Analysis

Using Microsoft Excel, the five trials at each power level were averaged to a single data point for each surgical platform. Next, a two-way ANOVA was performed in R to compare the effect of different surgical platforms and varying power level settings on energy output. Lastly, a post-hoc Tukey Honest Significant Difference (HSD) test was performed in R to assess statistically significant differences between the energy produced by different surgical platforms at a given power level.

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Table 1 Energy Transferred

Power Level	Alcon Centurion		Johnson & Johnson Veritas		Oertli CataRhex 3	
	Mean Energy (J)	SD	Mean Energy (J)	SD	Mean Energy (J)	SD
20%	13.44	2.45	66.74	6.50	12.46	5.91
40%	69.54	6.83	74.87	23.44	38.35	4.35
60%	107.71	11.79	94.90	29.87	45.17	8.05
80%	171.32	11.71	101.00	17.93	77.63	8.32
100%	132.88	7.26	127.47	40.99	75.80	12.31

Results

The mean energy output for the platforms is reported in J at 20%, 40%, 60%, 80% and 100% power and is listed in Table 1. The two-way ANOVA for difference between surgical platforms calculated an F value of 63.97 with two degrees of freedom ($P < 0.001$). For power level, the F value reported was 68.89 with four degrees of freedom ($P < 0.001$) (Figure 2). The Tukey's HSD test found a difference in mean energy output between the CataRhex 3 and Centurion of 49.10 J ($P<0.001$) and a difference between the CataRhex 3 and Veritas of 43.12 J ($P < 0.001$), when comparing mean energy output by the two platforms across all power levels (Figure 3).

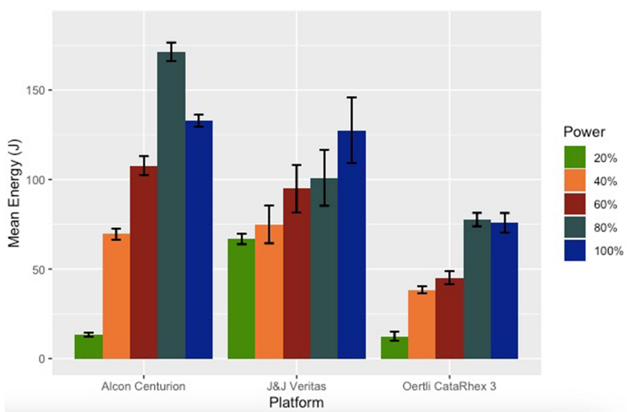

Figure 2 A bar graph showing the mean energy in joules produced by the three phacoemulsification platforms at 20%, 40%, 60%, 80% and 100% power.

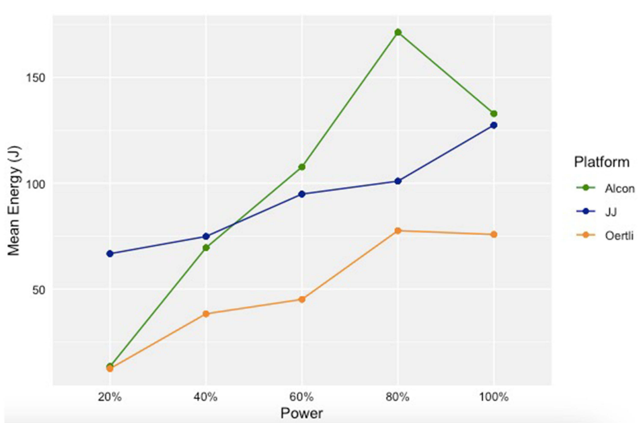

Figure 3 A line graph comparing the mean energy in joules produced at 20%, 40%, 60%, 80% and 100% power by the three phacoemulsification surgical platforms.

Table 2 Mean Difference in Energy Output Between Platforms

Power Level	CataRhex 3 and Centurion		Veritas and Centurion		CataRhex 3 and Veritas	
	Mean Energy Difference (J)	P value	Mean Energy Difference (J)	P value	Mean Energy Difference (J)	P value
20%	0.98	P=1.0	53.30	P<0.001	54.29	P<0.001
40%	31.19	P=0.21	5.34	P=1.0	36.52	P=0.06
60%	62.54	P<0.001	12.81	P=1.0	49.73	P<0.01
80%	93.69	P<0.001	70.33	P<0.001	23.37	P=0.66
100%	57.08	P<0.001	5.41	P=1.0	51.67	P<0.001

The Tukey HSD also compared the difference between the mean energy output of each platform at a given power level. The results are displayed in Table 2, showing that there was a statistically significant difference between energy output between surgical platforms at the same power level in the majority of comparisons, when using a P value of 0.05.

Discussion

Our results demonstrated that the amount of energy produced by phacoemulsification at a given power level showed a statistically significant difference between different surgical platforms, For example, 30 seconds of phaco at 80% power with the Centurion produced more than double the amount of energy than 30 seconds of phaco given the same parameters with the CataRhex 3. While this is one of the greatest differences between two platforms in the data, it underscores how vastly different energy production may be using identical parameters.

Another key finding is that the amount of energy produced did not increase linearly as the power level increased. For example, for 30 seconds of phaco with the CataRhex 3 the magnitude of energy increase between 60% and 80% power was more than four times greater than what was observed between 40% and 60% power. These data represent drastic differences in energy production between power levels, and document that energy production does not correlate linearly or proportionally with increasing power levels.

Furthermore, of the three surgical platforms, there was not one single surgical platform that consistently produced the most energy across all power levels; rather, the platform that produced the most energy differed by power level. To illustrate, at 40% power the Veritas produced the most energy of the three tested with 30 seconds of phaco; however, at 60% power the Centurion produced the most energy. It is important to point out that based on our data, the CataRhex 3 consistently produced the least amount of energy across each power level.

An unexpected finding was that an increased power level did not always create more energy during phaco within a given surgical platform. Interestingly, for two of the three platforms tested, the CataRhex 3 and the Centurion, more of the highest temperature increase was on average found at 80% power rather than at 100%. In past work, we have seen a plateau effect of efficiency above 80%, where trial runs at 100% resulted in decreased efficiency. This was felt to be due to excessive chatter events.[19] However, this finding brings into question whether there is another explanation, perhaps that over a certain amount of power input to the phaco handpiece, there may be a loss of energy transfer from the handpiece to the system over a certain threshold or some other mechanism whereby the larger amplitude phaco tip movements affect the measurements. It is also possible that by eliminating the inflow and outflow, there are some thermal-induced changes to the behavior of the piezoelectric crystals and their conversion to mechanical energy at the tip. Regardless, surgeons should be cautious when pushing platforms to extreme levels of power delivery, as it may not correlate with a more efficient surgery, even for dense lenses.

There are certain limitations to the generalizability of our findings to the clinical situation. First, our methods used a volume of 50 milliliters of distilled water in the double-walled calorimeter, which is a significantly greater volume than is present in the anterior segment. This was an adaptation that was needed to be able to submerge the phaco tip sufficiently into the liquid. However, it is important to understand that because the specific heat capacity is constant for a given substance and is denoted in the units of J/g°C, the amount of energy delivered into the system is agnostic to the volume of distilled water and therefore independent of the amount of liquid used.

To use the calorimetry calculations, it was important that the system be operated under complete occlusion. This is because these calculations required a specific, unchanging mass of liquid in the calorimeter, which would be unlikely to achieve if not under complete occlusion. Furthermore, if not under complete occlusion, BSS from the phaco platform would be introduced into the distilled water present in the calorimeter, thus making the specific heat capacity unknown due to having a mixture of both BSS and distilled water in the system. It is also noted that we conducted trials that were 30 seconds in length, which is longer than typical periods of occlusion would be during cataract surgery. This was important in order to provide enough time for heat generation that could be appreciably measured in 50 mL of water.

Lastly, our model did not differentiate between different forms of heat generated during the trials. We recognize that heat is generated not only from oscillation of the phaco tip, but also from fluid dynamics and the piezoelectric material and sleeve. We are unsure if, or to what level, we may have captured heat generation from cavitation, given that our calorimeter was opened to room air. Our study only captured the total amount of energy that was generated during the trial without respect to the individual mechanisms of energy production.

Conclusions

Our findings confirm the hypothesis that the amount of energy produced during phaco is not uniform across surgical platforms at identical settings, and that there is a statistically significant difference between the amount of energy produced by different phaco platforms. Our data do not serve to discover the exact amount of energy delivered at each power level, but rather to instruct surgeons that different surgical platforms deliver varying amounts of energy at identical settings. Importantly, we found that the amount of energy delivered does not increase linearly with increased power level, a finding we are not aware has been previously reported. Finally, at different power levels the platforms vary in which produced the most energy. These findings also may serve to initiate discussion about how energy delivery may be standardized between surgical platforms, and how manufacturers of these platforms can aid surgeons in understanding the energy While many institutions have only one phaco platform available for use, there are many institutions that have several options. Having data about energy transfer to the eye, and how it differs between platforms, can help a surgeon decide which platform to use. For institutions that have only one phaco platform available, this data can be important when deciding which platform to purchase next when the time comes. The way in which this information improves outcomes is that a large body of research, with several articles cited in this paper, demonstrates that introducing too much energy into the eye can lead to clinical complications produced during surgery with their respective platforms.

While this study focused on the use of calorimetry to compare the amount of energy transferred during phaco between different platforms, further studies using clinical outcomes can enhance this data. For example, Içöz et al have used clinical parameters such as corneal endothelial damage and number of complications to evaluate other surgical questions regarding phaco.[20,21] These further studies will build on the foundation established by this work.

Abbreviations

ANOVA, analysis of variance; BSS, balanced saline solution; c, specific heat capacity; C, Celsius; CDE, cumulative dissipated energy; HSD, Honest Significant Difference; J, joules; J/g°C, joules per gram degrees Celsius; m, mass; mL, milliliters; mL/min, milliliters per minute; mmHg, millimeters of mercury; phaco, phacoemulsification; Q, energy; T, temperature.

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Disclosure

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

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