Original Article

Comparison of thermal coagulation profiles for bipolar forceps with different cooling mechanisms in a porcine model of spinal surgery

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Abstract

Background: Coagulation accomplished using bipolar forceps is common in neurosurgery. Control of thermal spread from the forceps tips into surrounding neural tissues is a persistent concern, as neural tissues are especially vulnerable to heat injury. The purpose of our investigation was to compare the efficacy of cooling mechanisms for four different bipolar forceps and to understand thermal spread when coagulating vessels on the spinal cord.

Methods: Immediately following euthanasia, the dura mater of an *ex vivo* porcine model was opened to expose vessels on the spinal cord for coagulation. Temperature profiles were measured at generator power of 25 W and at fixed 5-second activation times. The bipolar forceps used in this study included regular stainless steel, titanium, heat-pipe embedded, and SILVERGlide forceps. Temperature was measured by micro-thermistor at the midpoint between the bipolar tips, and 1 and 2 mm away from the midpoint along the centerline. Statistical analysis was performed to evaluate temperature differences.

Results: Temperature profiles indicated that heat-pipe embedded forceps create the least amount of temperature increase and the highest normalized temperature decreasing slope after activation. The decreasing slope of SILVERGlide forceps is slightly higher than that of regular stainless steel forceps.

Conclusions: Bipolar forceps incorporating either heat-pipe embedded technology or SILVERGlide coating can effectively limit excessive thermal spread, thus decreasing potential injury to adjacent tissues when compared with standard stainless steel and titanium bipolar forceps. Of the two, heat-pipe embedded technology appeared safest, having better cooling efficiency at higher temperature.

Key Words: Bipolar, spinal cord, spine surgery, thermal injury

INTRODUCTION

In neurosurgery, coagulation is an important technique[23] and is often accomplished using bipolar forceps.[3] However, thermal spread from bipolar tips to adjacent tissue may result in inadvertent thermal injury, leading to unfavorable outcomes in a given operation. Because neural tissues are especially vulnerable to heat,[5] a better understanding of thermal spread in neurosurgical procedures is critical to ensure good surgical results.

The first electrosurgical system developed by Bovie and Cushing in 1926 was monopolar in design. Electrosurgical systems apply high-frequency electrical current to tissues to achieve desired clinical effects, including cutting and coagulating, depending on the applied waveform.[17] Electrical energy converts into thermal energy via Joule's First Law. According to Joule's First Law, $P = V \cdot I$, where P is the energy converted from electrical energy to thermal energy, V is the supplied voltage, and I is the electrical current travelling through the two electrodes. A monopolar system requires a returning electrode, which is usually a metal pad placed on the patient's back, to allow for completion of the electrical circuit. The spread of current caused by the returning electrode results in undesired thermal damage to surrounding tissues, which is of critical concern in neurosurgery. The concept of bipolar forceps was first presented by Greenwood in 1940[12] and remains the standard configuration to this day. Malis[16] later developed the first commercial bipolar coagulation system in the 1960s. This bipolar manner of delivering electrical current to tissue successfully restrains electrical energy and joule heating in a smaller volume of tissue.

This technique is still far from perfect, however, and other existing problems include adherence of tissue to the tips of coagulation forceps, the creation of an electric spark between forceps tips, and difficulties involved in removing carbonized clots and tissue from the tips. Most of these complications are due to overheating of the forceps tips.[10] Numerous attempts have been made to address these problems. To avoid the adherence of tissue, King and Worpole[15] used continuous saline drip to irrigate the forceps; this irrigation system was later automated by Dujovny *et al.*[7] A suction channel added to the irrigation system was modified by Scarff[21] to moderate bleeding prior to cauterization. Different algorithms to control energy delivery have been developed by others.[2,4,22] A variety of coating materials on the tips of bipolar forceps including silver,[14] gold,[18] nickel,[20] and titanium have been tested. Mikami *et al.*[19] compared three different coating materials. Another technique, active heat transfer (AHT), which uses fluid-filled heat pipes to continuously transfer heat away from the bipolar tips, has also been shown to reduce excessive heat build-up and minimize thermal spread.[1]

While overheating is an important issue that leads to other problems such as adherence and thermal damage, there has been a paucity of research examining thermal spread. Elliot-Lewis *et al.*[8,10] compared resultant temperatures for IsoCool bipolar forceps that incorporate AHT to conventional antistick bipolar forceps. Temperature was measured by thermocouple with a 1-Hz sampling rate and estimated by infrared thermal imaging. The experiment was performed in *ex vivo* bovine liver and *in vivo* rat brain. Another study compared thermal damage between devices using sheep spines and showed that AHT forceps caused significantly less thermally damaged area; however, the temperature was not measured.[9] Thermal profiling on a spinal model with higher temporal resolution is still needed to assess thermal spread more accurately.

In this study, we hypothesized that under the same electrosurgical generator power setting that applies the same amount of voltage (V in Joule's First Law), the forceps with the heat pipe or coating cooling mechanism will have less temperature increase due to the heat carried away by the cooling mechanism. Our study was designed to examine this hypothesis by measuring thermal profiles during coagulation using bipolar forceps with AHT and SILVERGlide coating cooling mechanisms as well as the traditional stainless steel and titanium forceps.

MATERIALS AND METHODS

The experiment was conducted in an animal surgery operating room at the University of Michigan Medical School. The procedure was compliant with the protocol approved by the University Committee on Use and Care of Animals. Two euthanized pigs (50% Duroc, 25% Yorkshire, and 25% Landrace) weighing 50 kg were used in this study.

Four different bipolar forceps were compared: (1) regular stainless steel bipolar forceps (DePuy/Codman and Shurtleff, Warsaw, IN); (2) titanium bipolar forceps (Covidien, Boulder, CO); (3) IsoCool (AHT) bipolar forceps (DePuy/Codman and Shurtleff); and (4) SILVERGlide bipolar forceps (Stryker, Kalamazoo, MI). The tips of these four forceps are shown in Figure 1, and their radii are 0.75, 1.0, 0.75, and 0.7 mm, respectively.

The titanium bipolar forceps feature a lighter weight and have less tendency for tissue adherence. However, titanium has a lower thermal conductivity than that of stainless steel and cannot conduct the heat away efficiently. The IsoCool bipolar forceps have embedded heat pipes within the shafts of the bipolar forceps to actively transfer heat away from its tips. The heat pipes contain a 2-phase working fluid. The fluid is evaporated in the distal end and diffuses to the proximal end with cooler temperatures. The vapor then condenses to liquid and flows back to the distal end. This phase-exchanging cycle is effective for heat transfer. The SILVERGlide bipolar forceps are made of stainless steel with tips coated in a silver alloy. The high thermal conductivity of the silver alloy allows heat dispersion faster than regular uncoated stainless steel forceps. The chemical inertia of the silver alloy also prevents tissue adherence or charring; thus, the SILVERGlide forceps are also known as antistick forceps. All the four forceps were powered by the same electrosurgical generator, Valleylab Force FX (Covidien). The power was set to 25 W for all trials.

A real-time subsurface temperature measurement technique developed by Dodde *et al.*[6] was used in our study. We used micro-thermistors (Model #56A1002-C8; Alpha Technics, Irvine, CA) that have an outside diameter of 0.46 mm. The measurement tolerance is ± 0.1°C at 25°C with a time constant of 250 ms. Voltage differences across thermistors were recorded using a Wheatstone bridge circuit, and the signals were transmitted and converted to temperatures using LabVIEW System Design Software (National Instruments, Austin, TX) via a data acquisition system (PXI-1033; National Instruments). The sampling rate was 100 Hz. A low-pass resistance-capacitance (RC) filter with cutoff frequency of 3.38 Hz at 25°C (R: 10 kΩ and C: 4.7 μF) was connected to each Wheatstone bridge to eliminate high-frequency noise induced by the electrosurgical generator and the 60 Hz alternating current noise. Polycarbonate fixtures were created for each of the forceps tested to ensure temperature measurements were recorded at precise locations [Figure 2a]. As illustrated in Figure 3, all the three measuring positions were along the centerline between the tips of forceps, and were either midpoint (thermistor #1), or 1 mm (thermistor #2) or 2 mm (thermistor #3) away from the midpoint along the centerline of the forceps tips. Forceps tips were fixed at 2-mm spacing by use of another fixture [Figure 2b]. The output voltage and current supplied by the electrosurgical generator were also measured by a voltage probe (Model #1165A; Agilent Technologies, Santa Clara, CA) and a current probe (Model #1047A; Agilent Technologies), respectively. The sampling rate for these electrical data was 5 MHz. The measured voltage and current data were converted to their root mean square values, V_{rms} and I_{rms}, respectively. The power consumption rate was then calculated by multiplying V_{rms} by I_{rms}.

The experiment was carried out immediately after euthanizing the pig. This *ex vivo* experimental set-up for biopolar coagulation was consistent for all tests. The goal was to compare the thermal profiles of the four forceps under the same conditions; the *ex vivo* porcine spinal cord configuration is adequate to achieve this goal. The dura mater was opened to expose vessels on the spinal cord [Figure 4]. Vessels with a diameter between 0.3 and 0.5 mm were chosen for coagulation. The diameter was measured by a digital caliper (Model # 500-195-20, Mitutoyo, Aurora, IL). Prior to each bipolar coagulation, the spinal cord was irrigated with water to maintain proper moisture on the spinal cord surface. The power of the generator was set at 25 W. Activation time of the generator was fixed at 5 seconds to simulate a moderate coagulating situation.[1] The order of coagulation was randomized to neutralize any experimental uncertainty.

The number of coagulations performed was determined based on a preliminary study; a total sample size of $n = 24$ (6 trials per forceps) was required to achieve statistical power of 95%.[11] In our study, 36 trials were conducted (9 per forceps). One-way analysis of variance (ANOVA) was carried out for midpoint, 1, and 2-mm measurement points to determine whether the 5 seconds average temperature-increasing rate during varied among forceps. Differences indicated by ANOVA were tested using Tukey-HSD (Honest Significant Difference) test for *post hoc* multiple comparisons. Statistical significance was set at $P < 0.05$. All analyses
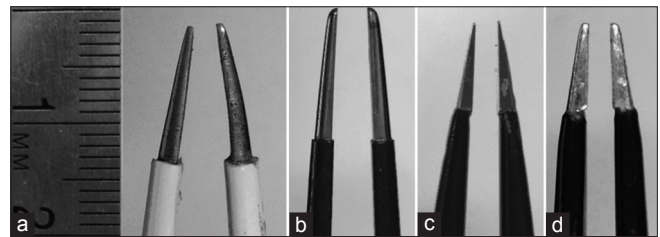

Figure 1: (a) Regular stainless steel, (b) Titanium, (c) AHT, and (d) SILVERGlide forceps tips used in this study
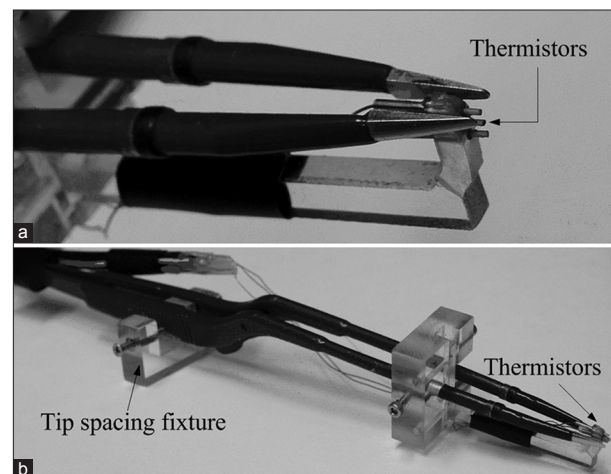

Figure 2: Bipolar forceps showing (a) Fixture for thermistors and (b) Tip-spacing fixture
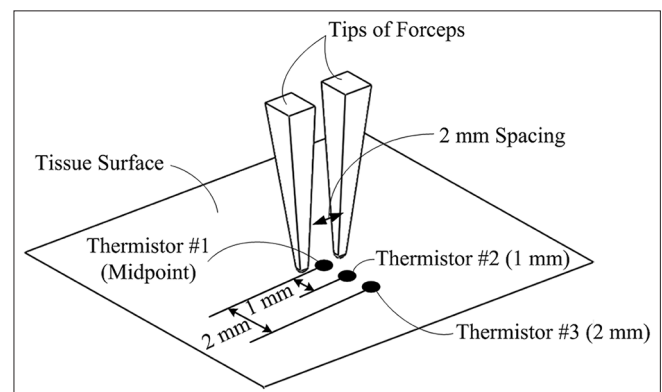

Figure 3: Schematic illustration of temperature measurement points

were performed using IBM SPSS Statistics for Windows, version 20 (IBM Corp., Armonk, NY).

RESULTS

Figure 5 shows a comparison of average temperature-increasing rate (°C/s) during the 5-second coagulation for all the three measurement locations among the four forceps. One-way ANOVA showed that the temperature-increasing rate significantly varied among forceps at all the three measurement points (midpoint: $F_{(3, 32)} = 37.1$, $P < 0.001$; 1 mm: $F_{(3, 32)} = 14.7$, $P < 0.001$; and 2 mm: $F_{(3, 32)} = 10.7$, $P < 0.001$). *Post hoc* multiple comparison tests were then carried out to compare the difference of temperature-increasing rate between any pair of forceps. The regular stainless steel forceps had a significantly higher temperature-increasing rate than both AHT forceps and SILVERGlide forceps at all the three measurement points (Tukey's HSD = midpoint: $P < 0.001$ and $P < 0.001$; 1 mm: $P < 0.001$ and $P < 0.001$; 2 mm: $P < 0.001$ and $P = 0.001$, respectively). The titanium forceps also had a significantly higher temperature-increasing rate than AHT forceps and SILVERGlide forceps for all the three measurement points (Tukey's HSD = midpoint: $P < 0.001$ and $P < 0.001$; 1 mm: $P = 0.003$ and $P = 0.001$; 2 mm: $P = 0.007$ and $P = 0.024$, respectively). There were no differences between the regular stainless steel forceps and titanium forceps at any of the three measurement points. There were also no differences between the AHT forceps and the SILVERGlide forceps at any of the three measurement points. Figure 6 compares the average temperature-increasing rate and measured power consumption rate among the four forceps. Under the same power setting (25 W), the measured output voltage (V_{rms}) was 87 V for all trials. There was no statistical difference in power consumption rate among the four forceps ($P = 0.15$).

Line graphs in Figure 7 show temporal temperatures at the three thermistor positions using four different bipolar forceps during coagulation of vessels on porcine spinal cord. Each temperature curve is the average result of the nine coagulations. The starting internal temperature of the porcine spinal vessel was 25°C. For thermistor #1, the temperature increased about 34°C, 30°C, 12°C, and 15°C for the regular, titanium, AHT, and SILVERGlide forceps, respectively, at the end of each 5-second activation cycle. The temperature then dropped after activation. Temperature of the regular forceps decreased most rapidly, as it had the greatest temperature gradient to the ambient environment. For thermistor #2, the temperature increased by about 24°C, 21°C, 10°C, and 6°C for regular, titanium, AHT, and SILVERGlide forceps, respectively, at the end of the activation cycle. Temperature of the regular and SILVERGlide devices

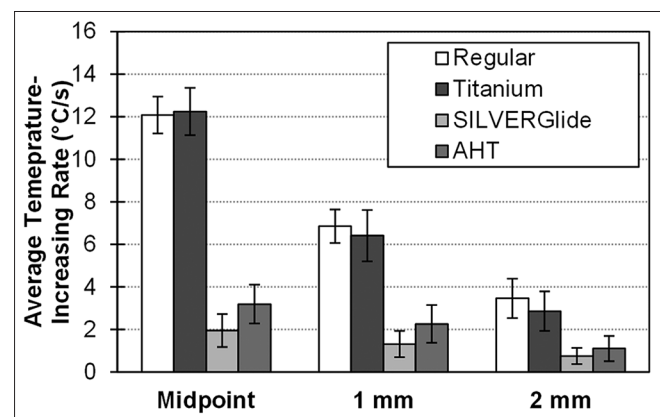**Figure 4: Process of coagulating a vessel on porcine spinal cord**

Figure 5: Average temperature-increasing rate over 5 seconds for the four forceps at three measurement positions
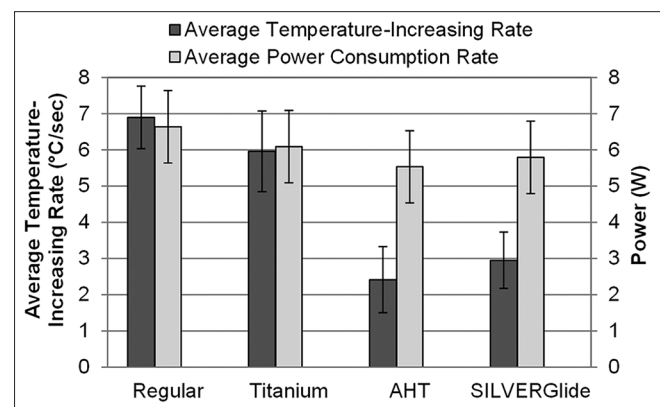

Figure 6: Bar graph comparision of average temperature-increasing rate and average power consumption rate among four bipolar forceps

then kept increasing slowly for about another 1 and 2.5 seconds, respectively, demonstrating that heat was still being conducted from the midpoint. Temperature of the AHT device did not increase after activation as the temperature gradient was small. For thermistor #3, temperature of the regular and SILVERGlide devices increased over the whole 10-second recording period,
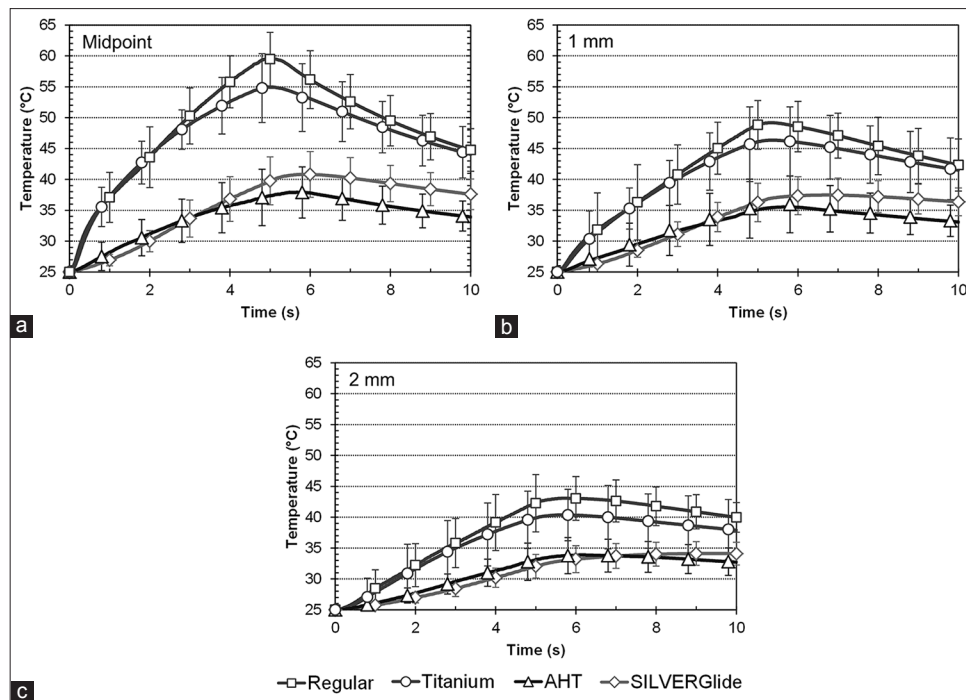
Figure 7: Line graphs illustrating temporal temperature profiles for four forceps at (a) Midpoint, and (b) 1 mm and (c) 2 mm away from midpoint along the centerline

while temperature of the AHT device remained at roughly the same level after activation.

DISCUSSION

In this study, we compared temperature profiles when coagulating vessels on porcine spinal cord using bipolar forceps with different cooling mechanisms. The results provide a clear comparison among the four devices studied. The regular stainless steel forceps produced the highest temperatures at all the three thermistor locations, while the AHT forceps had lowest temperature increases. Temperatures resulting from the titanium forceps were slightly lower than the regular stainless steel forceps. SILVERGlide forceps showed slightly higher temperature increases than the AHT forceps. The AHT forceps, which uses heat pipes, effectively conducted heat away from the tips. As indicated by the ANOVA analyses, the AHT and SILVERGlide forceps have significantly lower temperature-increasing rates compared with those of regular stainless steel and titanium forceps. The slow temperature-increase rate results not only in reduced thermal spread, but also in better control of coagulation, and lessens the tendency for overheating tissue.

As shown in Figure 6, with the same supplied voltage and similar power consumption, the heating efficiency of each forceps to convert electrical energy to thermal energy is quite different. The ratios of average temperature-increasing rate to the average power consumption rate for regular stainless steel, titanium,

AHT, and SILVERGlide forceps are calculated to be 1.04, 0.98, 0.42, and 0.53 (°C/s·W), respectively. This difference in heating efficiency may be contributed to both cooling mechanism and forceps design (geometry and material). This result demonstrates that in order to achieve the same amount of heating ability, AHT and SILVERGlide forceps require much higher energy input. Under the same voltage level (as in this study), AHT and SILVERGlide forceps require longer activation time to reach the same level of tissue temperature and thus, allows more heat to dissipate.

To further compare the cooling efficiency of each forceps, we observed the temperature changes after terminating the power, when there is no effect of heating. The heat generated then transfers away from the coagulation region via three pathways: (1) conduction to adjacent tissue, (2) conduction to the forceps, and (3) convection into ambient surroundings. Figure 8a shows temperature decreases at midpoint after reaching the maximum temperature. The maximum temperature occurred at 5.0, 5.0, 5.66, and 5.86 seconds for regular stainless steel, titanium, AHT, and SILVERGlide forceps, respectively. The slope of each curve is the temperature-decreasing rate via these three pathways. For regular stainless steel and titanium forceps, the slopes are steeper because these two forceps have a higher temperature gradient (i.e., the temperature difference between the midpoint and 1-mm point). It is known that the rate of heat conduction is proportional to both the spatial temperature gradient and thermal conductivity of the material.[13] The slope

resulting from regular stainless steel forceps is slightly higher than that of titanium forceps because stainless steel has higher thermal conductivity than titanium and can conduct heat more efficiently. The AHT and SILVERGlide forceps have lower slope due to the smaller temperature gradient. In contrast, the temperature of AHT and SILVERGlide forceps continued increasing for 0.66 and 0.86 seconds after activation stopped because the effect of the heat transferred from the tissue around the tip to the midpoint between tips is larger than that of the heat conducting to the tissue that is far from the tips.

To fairly evaluate the effect of cooling mechanisms, the temperature profiles have to be normalized to compensate for the effect of the difference in spatial temperature gradient among forceps. Spatial temperature gradient is defined as the temperature difference between the midpoint and 1 mm away from the midpoint at 5 seconds. Spatial temperature gradients for regular stainless steel, titanium, AHT, and SILVERGlide forceps are 10.7°C, 8.84°C, 2.38°C, and 3.50°C, respectively. The temperature profiles in Figure 8a were normalized by these temperature gradients. Figure 8b shows the normalized temperature profiles, which mean the temperature change per degree of spatial temperature gradient. The temperature slope in Figure 8b indicates the ability of forceps to absorb thermal energy by conduction. Temperature slopes of the four forceps are summarized in Table 1. The AHT forceps have the highest decreasing slope and is 41.8% higher than the stainless steel forceps. When the forceps absorb more thermal energy, less energy is transferred to adjacent tissue. The slope of SILVERGlide forceps is slightly higher (5.3%) than that of regular stainless steel. The titanium forceps have the lowest slope (12.6% less than regular stainless steel) and the worst performance to absorb thermal energy due to its low thermal conductivity.

The AHT forceps use a 2-phase working fluid that is vacuum-sealed in the heat pipes embedded in the forceps shaft.[8] The fluid has a working temperature range that varies by the type of fluid and level of vacuum.[24] The working fluid also needs time to accumulate enough energy to overcome the latent heat in order to evaporate the working fluid. Before the temperature reaches the working range, the fluid inside the heat pipe cannot be evaporated and thus, the AHT forceps do not show superior performance below this working temperature range. As shown in Figure 7a, for the first 3 seconds, the temperature of AHT forceps is higher than that of SILVERGlide forceps. This is because the silver coating on the surface of SILVERGlide forceps has a higher thermal conductivity than that of the AHT forceps. Before the heat pipe in the AHT forceps reaches working temperature and response time, the SILVERGlide forceps performs better for conducting heat away. Once the working temperature range is reached, the AHT forceps can then conduct heat more efficiently.

Results of our study performed on porcine spinal cord are consistent with the results obtained in a previous study on coagulation in *ex vivo* calf liver.[10] In spinal surgery, neurosurgeons tend to use a lower power setting to prevent thermal damage. We used 25 W for our study, while previous studies[8,10] used much higher power at 35 and 50 W. It can be expected that with a higher power, a larger temperature difference among devices can be seen. However, using a low power setting, we still found noticeable differences.

The major limitation to our study is that the experiment was not conducted with live animals. Thus, the efficacy of coagulation could not be studied. However, the main purpose of this study was to compare temperature profiles and the effect of cooling mechanisms. For the

Table 1: Temperature slopes and relative efficiency of study forceps designs

Forceps	Normalized temperature-decreasing slope	Relative efficiency* (%)
Regular stainless steel	1.17	-
Titanium	1.02	−12.6
Active heat transfer	1.66	+41.8
Silver glide	1.23	+5.3

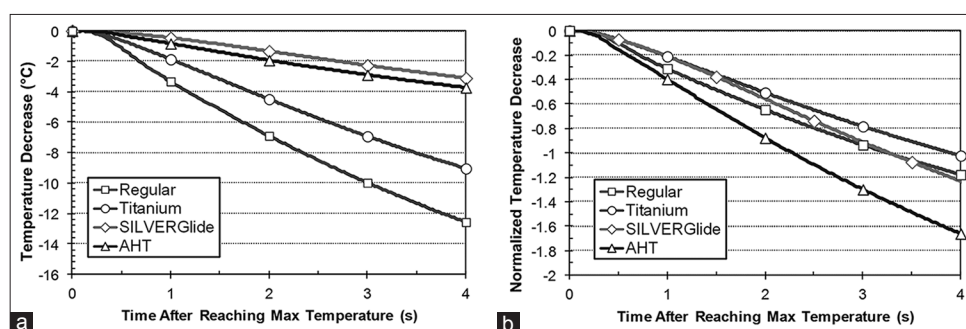*Relative efficiency is compared with the regular stainless steel forceps

Figure 8: Line graph illustrating (a) Temperature decreases in four forceps after reaching maximum temperature and (b) Normalized temperature decreases

AHT device, the low temperatures generated may not coagulate the vessel effectively, thereby requiring a longer activation time. This may be a concern for surgeons and requires further study.

CONCLUSIONS

Based on this porcine spinal cord study, with the same energy input, the AHT and SILVERGlide forceps produced the least amount of thermal spread compared with regular stainless steel and titanium forceps. The AHT and SILVERGlide forceps also show a slower temperature-increasing rate, which allows a better control of temperature increase, but may require longer coagulation time or higher power setting. The stainless steel and titanium forceps have a higher temperature-increasing rate and are better in the case of heavy bleeding. The AHT forceps have better cooling efficiency than SILVERGlide forceps at higher temperatures. Therefore, it would appear to be safer to use AHT forceps when hemostasis needs to be performed adjacent to vital neural tissues. Future study may incorporate external cooling device to stainless steel or titanium forceps to maintain the ability to coagulate vessel quickly and minimize thermal damage to the adjacent tissue.

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Commentary

This study deals with temperature profiles using four different bipolar forceps with three different tip sizes using 25 Malis units with 5 second activation time. This study is performed on a freshly euthanized porcine spinal cord model, and shows that the lowest temperatures are achieved with the AHT forceps (with cooling tubes installed). This study also notes that "The AHT and silver glide forceps show a slower temperature increasing rate, which allows better control of temperature, but may require longer coagulation time or higher power setting." The study is precise in its goals, well performed, and honest in its conclusions. Of note, is that the 5 second coagulation time used in the study, is an eternity of coagulation time in actual usage. Optimally, in the OR, it is good an accepted medical practice to localize the bleeder with the use of compressive cotton sponges, and irrigation; and to coagulate the vessel in short, staccato type coagulation pulses, evaluating results between coagulation pulses. This manuscript accurately and realistically describes the properties of four different forceps, but also notes realistically, that the AHT forceps may require higher power settings, along with longer

coagulation times than forceps without these cooling mechanisms. This study also suggests that further study may be indicated to determine if in use in realistic situations, the AHT forceps, which may require higher settings along with longer coagulation times, have any functional advantage over forceps without the cooling mechanisms. Specifically, with further evaluation, variation of bipolar power and coagulation times with a stainless steel and titanium forceps without cooling mechanisms, may achieve the same results as the self-cooled forceps, which in comparison to the former forceps may require longer coagulation times and higher powers. At the end of the day, with fuller evaluation of various bipolar forceps types, in more realistic emulations of OR situations, it may be found that, as in many other surgical and life settings, it is not what is under the hood, but who is behind the wheel.

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