Cool Mist Irrigation Improves Heat Dissipation during Surgical Bone Drilling

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Abstract

Objective High-speed drilling generates heat in small cavities and may pose a risk for neurovascular tissues. We hypothesize that a continuous pressurized cold mist could be an alternative approach for better cooling during drilling of bone to access cranial lesions. This study aims to examine this idea experimentally.

Design Ex-vivo drilling tests with controlled speed, feed, and depth were performed on cortical bone samples. Thermocouples were embedded underneath the drilling path to compare the temperature rises under mist cooling (at 3°C, < 300 mL/h) and flood irrigation (at 22°C, > 800 mL/h).

Results A significant difference exists between these two systems (p value < 0.05). The measured temperature was ~ 4°C lower for mist cooling than for flood irrigation, even with less than a third of the flow rate.

Conclusion Experimental data indicate the capability of mist cooling to reduce heat generation while simultaneously enabling flow reduction and targeted cooling. An improved field of view in an extremely narrow access corridor may be achieved with this technology.

Keywords

- high-speed drilling
- endonasal drilling
- irrigation
- thermal injury

Introduction

The endoscopic endonasal approach (EEA) creates exposure optimal for the surgical treatment of malignancies involving the ventral and ventral-lateral skull base.¹ Neurosurgeons and otolaryngologists can access deep lesions of the head and neck through endonasal routes that, in the past, often required large open exposures. This approach affords certain benefits to the patients in the sense that less normal tissue is traumatized, and visualization, in many instances, is enhanced relative to traditional open techniques. Drilling of

the frontal, ethmoid, sphenoid, and clival portion of the occipital bones to access lesions of the anterior cranial base is commonly performed through the EEA.

The drilling procedure requires irrigation because the heat generated by high-speed drills, which typically operate at 50,000 to 75,000 RPM, can cause thermal injury to surrounding vascular and nervous tissues.² Such damage can result in catastrophic injuries, particularly when the patient has suffered prior damage due to compression or irradiation. Nearby structures particularly vulnerable to thermal damage include the optic nerves, internal carotid arteries, maxillary nerves,

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vidian nerves, and the contents of the cavernous sinuses. Average body temperature is 37°C, and nerve injury is known to occur above 43°C.³ Conservatively, there is only a 6°C safe operating range during drilling. Concern for thermal injury has been raised and documented in the literature; anecdotally, this is one of the risks most feared when performing such procedures. Shaw et al⁴ found that the optic nerve sees high temperatures during high-speed drilling that may damage the nerve and may be the cause of vision loss in surgical patients. Abbas et al⁵ found that during mastoid bone drilling, the facial nerve is also exposed to temperatures high enough to cause irreversible damage. Both studies indicated that irrigation to the surgical field while drilling is critical to limit temperature rise, but neither quantitated its efficacy.

Irrigation by intermittently flooding the surgical field with saline is one common practice, necessary for both temperature control and visualization. Although intermittent flood irrigation likely helps to mitigate temperature rise during drilling, there is no quantitative study demonstrating that peak temperatures at the drilling site do not pose a risk for thermal injury. Shaw et al⁵ caution that adequate irrigation should be used to reduce thermal injury, and frequent use of irrigation could impair the field of view during the operation and interrupts workflow.⁶ To address these issues with a single solution, we propose a focused cool mist irrigator, in which the saline is cooled and slightly pressurized for better cooling and targeted irrigation. As such, the fluid flow rate can also be greatly reduced.

Methods

For a quantitative comparison to current common practice, temperature behavior surrounding the drill–bone interface was measured with thermocouples embedded into the bone sample. This method could provide a more accurate temperature measurement than using an infrared camera to capture surface temperature⁶ because surface temperature can be skewed by the presence of surface debris and irrigation; in addition, the structures at risk for thermal injury are typically deep to the bone surface at the time of drilling, and thus surface temperature is a potentially inaccurate reflection of heat dissipation in the relevant regions.

The mist cooling device tested in this study consists of a nozzle, designed to accommodate the handedness of the surgeon, coupled to a surgical high-speed drill for use as a single unit. Fluid is delivered via a pump and mixed with compressed air to form a mist. Both fluid and air are pre-cooled to ~ 0°C for the generation of low-temperature mist, as the design chart illustrated in ►Fig. 1.

The drilling system used to conduct the tests includes a Medtronic Midas Rex Legend System EHS Stylus drill (Model EM200), an electric console to power the drill (Model EC300), and a 3-mm diamond abrasive transnasal skull base bur (Model TN30MCD). Drilling was performed using a computer controlled three-axis linear stage system (Siskiyou Model 200cri) with 1-μm resolution to maintain the drilling condition for multiple tests, such as feed rate and engaged depth. The overall setup is shown in ►Fig. 2, where the drill, bone sample, and mist cooling nozzle are identified.

Fig. 1 Schematic configuration of the mist cooling device based on the current irrigation design.

The drill was mounted 30 degrees (θ) relative to the bone surface. For the purpose of comparison, bovine femur bone was chosen to simulate the cortical bone of the cranial base for reproducibility of the experimental environment. Bone samples were machined on a mill to a block shape with dimensions of 25 mm × 25 mm × 4 mm. Four 1-mm-diameter holes were drilled 5 mm apart into each test sample. The two holes on the ends were drilled through and used as a reference to align the drill; the two holes in the middle were drilled to 530 μm from the testing surface for embedding the thermocouples (Omega Engineering, Model 5TC-TT-K-36-36). A prepared bone sample is depicted in ►Fig. 3. The thermocouples were exposed to the drill during the fifth stroke of the test.

Drilling tests were conducted at two different fluid flow rates (200 and 300 mL/h) for mist cooling and a continuous flood irrigation condition (~ 800 mL/h). Mist temperature measured at the nozzle was ~ 3°C, whereas flood irrigation was measured at 22°C. Note that this study was aimed at comparing two individual systems; thus temperature and flow rate were not controlled as variables. In the experiment, each condition was repeated four times, for a total of 12 tests. The feed rate (90 mm/min), drill speed (70,000 RPM), and air pressure (69 kPa, or 10 psi) were fixed for all tests. A five-stroke paintbrush motion was used for each test, starting with a reverse stroke (X direction in ►Fig. 2). The depth of cut

Fig. 2 Experimental setup with the main components labeled. Thermocouple holes were drilled up to 530 μm from the bone surface.

Fig. 3 Bovine samples used for drilling and temperature measurement. Left image is the bottom surface where the thermocouples are inserted; right image is the top surface where the drilling occurs. Two holes on the end were used as reference holes to align the drill, and two holes in the middle were used to embed the thermocouples 530 μ m from the surface. All holes were drilled 5 mm apart.

for each stroke was 100 μ m, for a total of 500 μ m. Thus 30- μ m clearance above the thermocouple holes existed at the end of each drilling run. Sampling rate of the temperature data was 5 Hz.

For data analysis, each measurement was normalized by shifting the temperature profile to an initial temperature of 20°C. Peak temperature at each stroke was extracted from the larger temperature response between two thermocouples embedded at the same depth. An unpaired *t* test was conducted to compare results between each condition, with *p* < 0.05 representing statistical significance.

Results

Maximum temperature occurs when the last drilling stroke passes above the thermocouple. ► **Fig. 4** summarizes the average temperature at each stroke for the two flow rate conditions of mist cooling and the flood irrigation condition.

Overall, mist cooling exhibits lower temperatures across five strokes than those of flood irrigation. The peak temperature (mean $\pm$ standard deviation) was highest for flood irrigation (27.8 $\pm$ 0.9°C). The peak temperature was significantly lower for mist cooling and similar for 200 mL/h and

Fig. 4 Average temperature at each of the drilling strokes for the three flow rate conditions (200 mL/h, 300 mL/h, and 800 mL/h) shows that bone temperature during mist cooling is equal to or less than bone temperature during flood irrigation.

300 mL/h flow rates: 24.0 $\pm$ 2.9°C and 24.5 $\pm$ 2.4°C, respectively. A significant difference exists between flood and mist cooling both at 200 mL/h (*p* = 0.047) and at 300 mL/h (*p* = 0.044). No difference was found between 200 and 300 mL/h mist cooling (*p* = 0.78).

Discussion

Mist cooling is a novel approach to irrigation by mixing compressed air and fluid to form a mist that is applied at the drill–bone interface. Based on these experiments, cool mist irrigation reduces temperature spikes from 8°C to 4°C, thus limiting the risk of thermal injury to within the 6°C safety zone. Although thermal injury to neural tissue is believed to occur at temperatures > 43°C, the occurrence of permanent damage depends on the total exposure time under high temperature (i.e., thermal dose⁴). Because mist cooling allows for continuous irrigation, spikes in temperature are better controlled than using intermittent irrigation—in our experiments, this control is the difference between safety and thermal injury to adjacent nerves.

From a physics standpoint, fluid in a mist form allows for a greater surface area per volume of irrigant to contact the drilled surface. Importantly, mist cooling thus requires a much smaller volume of fluid, potentially improving the field of view in an extremely narrow access corridor. The ability to precool the irrigation fluid is another important feature of this technology, serving to enhance heat exchange. The fluid used to form a mist is cooled to < 10°C, which serves to reduce the absolute temperature at the drill–bone interface when applied in a focused, directed manner. However, simply using cold flood irrigation is untenable in clinical practice due to the effects on total body temperature and the local coagulation cascade.

The flow rate of mist cooling is a variable that requires more study to optimize. Although flow rates of 200 mL/h and 300 mL/h did not exhibit a significant difference, upper and lower limits may exist to the capacity for cooling relative to the volume of irrigant delivered. In our experiments, the mist cooling device demonstrated potential value in improving visualization. Because of much smaller fluid volumes and continuous administration via a nozzle integrated with the drill, we observed an improved field of view in an extremely narrow access corridor, although this experience was purely anecdotal.

Conclusions

According to the results from drilling bovine bone samples with controlled feed and depth, mist cooling reduces peak temperature rise from 8°C (under conventional irrigation methods) to 4°C using only a third of the volume of irrigation. Cool mist irrigation provides better local temperature control by targeting the point of drill-to-bone contact; in the process, it has the potential to reduce the risk of thermal injury to adjacent structures including vasculature and neural elements. Currently, the nozzle used for testing the device has a shape designed to fit a commercial drill. Finally, drilling tests in anatomically relevant

conditions are necessary to refine the application of our cool mist irrigation system for clinical use.

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