American Journal of Emergency Medicine 34 (2016) 887–894

Contents lists available at ScienceDirect

American Journal of Emergency Medicine

journal homepage: www.elsevier.com/locate/ajem

Brief Report

Rapid and selective brain cooling method using vortex tube: A feasibility study☆,☆☆

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ARTICLE INFO

Article history:
Received 14 September 2015
Received in revised form 3 February 2016
Accepted 4 February 2016

ABSTRACT

Vortex tubes are simple mechanical devices to produce cold air from a stream of compressed air without any moving parts. The primary focus of the current study is to investigate the feasibility and efficiency of nasopharyngeal brain cooling method using a vortex tube. Experiments were conducted on 5 juvenile pigs. Nasopharygeal brain cooling was achieved by directing cooled air via a catheter in each nostril into the nasal cavities. A vortex tube was used to generate cold air using various sources of compressed air: (I) hospital medical air outlet (n = 1); (II) medical air cylinders (n = 3); and (III) scuba (diving) cylinders (n = 1). By using compressed air from a hospital medical air outlet at fixed inlet pressure of 50 PSI, maximum brain-rectal temperature gradient of −2°C was reached about 45–60 minutes by setting the flow rate of 25 L/min and temperature of −7°C at the cold air outlet. Similarly, by using medical air cylinders at fill-pressure of 2265 PSI and down regulate the inlet pressure to the vortex tube to 50 PSI, brain temperature could be reduced more rapidly by blowing −22°C ± 2°C air at a flow rate of 50 L/min; brain–body temperature gradient of −8°C was obtained about 30 minutes. Furthermore, we examined scuba cylinders as a portable source of compressed gas supply to the vortex tube. Likewise, by setting up the vortex tube to have an inlet pressure of 25 PSI and 50 L/min and −3°C at the cold air outlet, brain temperature decreased 4.5°C within 10–20 min.

1. Introduction

Hypothermia is known to reduce the chances of brain tissue damage when oxygenated blood supply to the brain is diminished as may occur during ischemic or anoxic events such as cardiac arrest [1,2]. The neuroprotective benefits of hypothermia have been linked to the time to initiate cooling after injury, depth of cooling and re-warming rate [3,4]. The general agreements among clinicians are early cooling initiation within the treatment window after injury, and gradual rewarming (i.e., 0.1°C/h-0.4°C/h) [5,6]. The optimum target temperature for therapeutic hypothermia is still uncertain. Although some clinical studies indicate that the temperature range associated with better outcomes appears to be 32°C to 35°C [7,8], a recent study revealed no significant difference between hypothermic and near-normothermic treatment groups (33°C and 36°C) in patients after cardiac arrest in terms of their survival and neurologic outcome [9]. Moreover, cooling the whole body below 34°C can induce severe complications including shivering, skin erythema, renal failure, coagulopathy, pulmonary hypertension and increased mortality [10]. Moreover, it may decrease perfusion and oxygenation by impairing myocardial contractility, reducing cardiac output and making the heart more prone to arrhythmia [11]. Consequently, to maximize neuroprotective effects such as preventing inflammatory cascades in brain yet minimize systemic complications, delivery of selective cerebral hypothermia would be advantageous.

Cooling the nasopharynx may offer the capability to cool the brain selectively due to anatomic proximity of the internal carotid artery to the cavernous sinus. Furthermore, cerebrospinal fluid chilled at the basal cistern cools the whole brain through the cerebrospinal fluid circulation. Vortex tubes, also known as Ranque-Hilsch vortex tubes [12,13], are very simple mechanical devices to produce cold and hot air from a stream of compressed air without any moving parts, which are typically used for commercial low temperature applications such as cooling of electrical parts, control units, cutting tools and mechanical, electronic or electrical components under severe thermal stresses [14]. In this report, we have investigated whether spraying cooled air produced by a vortex tube into nasal cavities is an effective and simple cooling method to selectively reduce and maintain brain temperature

☆ Conflicts of Interest: MFB, LK, and T-YL are inventors on patent application PCT/CA2015/050,216 submitted on March 4, 2013, describing the selective brain cooling method.

☆☆ Sources of Funding: Lawson Health Research Institute.

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http://dx.doi.org/10.1016/j.ajem.2016.02.001
0735-6757/

on normal juvenile pigs. Furthermore, we examined different sources of compressed breathable gas supply to the vortex tube and outputting cooled air from the vortex tube.

2. Methods and apparatus

2.1. Animal preparation and experimental procedure

Experiments were conducted on 5 juvenile Duroc pigs with an average age of 2 to 3 weeks and an average weight of 14 kg ± 4 kg. All animal experiments were approved by the Animal Use Subcommittee of the Canadian Council on Animal Care at the University of Western Ontario. Animals were obtained from a local supplier on the morning of the experiment. Piglets were induced with 4% isoflurane and then maintained on 2% to 3% for preparatory surgery. The 4% isoflurane provided a rapid induction of anesthesia within 15 to 30 seconds, whereas the 2% to 3% isoflurane maintained surgical anesthesia, allowing surgical procedures to be performed without any physiological signs of pain or changes of hemodynamic parameters. A tracheotomy was performed and the animal was ventilated with a volume-controlled mechanical ventilator to deliver oxygen/medical air mixture (2:1). A femoral artery was catheterized to monitor heart rate (HR) and mean arterial blood pressure (MAP) and to intermittently collect arterial blood samples for gas ($Paco_2$, Pao_2), pH and glucose analyses. Arterial CO_2 tension ($Paco_2$) was monitored throughout the experiment, either directly by blood gas or by the end-tidal CO_2 tension measurements, and maintained at normocapnia between 37 and 42 mmHg by adjusting the breathing rate and volume. Arterial oxygen tension (Pao_2) was maintained at a level between 90 and 130 mmHg by adjusting the ratio of oxygen to medical air. Blood glucose was monitored intermittently and if it fell below 4.5 mmol/L, a 1 and 2 mL infusion of 25% glucose solution was administered intravenously. Rectal temperature was recorded from a rectal probe inserted to 3 to 4 cm from the anal margin. Brain temperature was also measured continuously with a thermocouple probe. A burr hole 1.5 cm posterior to the bregma along the mid-line was made in the skull with a Dremel tool. The needle thermocouple probe was inserted through the burr hole into the brain to a depth of 2 cm from the brain surface to measure brain temperature. After surgery, each pig together with a recirculating heated water blanket were wrapped with linen blankets to keep core temperature at 38.5°C ± 0.5°C and anesthesia was maintained on 1% to 2% isoflurane.

2.2. Method of nasopharyngeal brain cooling

A schematic of a typical vortex tube is shown in Fig. 1. It comprises an air inlet nozzle, a vortex generation chamber, a cold-end orifice, a hot-end control valve and a tube. Compressed air enters through the inlet nozzle. The air passes through a generation chamber which spins the air centrifugally along the inner walls of the tube at a high rate of angular velocity (1,000,000 RPM) toward the opposite end of the tube where a control valve allows some of the air to escape. The remaining air is forced back through the center of the incoming air stream to exit as cold air through the cold air outlet next to the compressed air inlet nozzle. The fraction of compressed air exiting as cold air is called the Cold Fraction. The following sources of compressed breathable gas supply to the vortex tube [15] (Adjustable cold air gun, ITW Vortec, Ltd)(Fig. 2) were tried:

I. Hospital medical air outlet at fixed outlet pressure of 50 PSI (n = 1)(method I);
II. Medical air cylinders with the capacity of 232 ft^3 at fill-pressure of 2265 PSI (supplied by L'Air Liquide, Ltd) at variable vortex tube inlet pressure of 10, 25, 35 and 50 PSI (n = 3) (method II);
III. Scuba (diving) cylinders with the capacity of 100 ft^3 at fill-pressure of 2640 PSI at vortex tube inlet pressure of 15 and 25 PSI (n = 1) (method III).

A custom-made catheter (made from Polyvinyl Chloride, PVC), coated with 2% lidocaine gel for anesthesia and better contact with turbinate in the nasal cavity, was inserted 8 to 10 cm into each nostril. The nasal catheter comprises a tubular body defining a lumen and an open end in continuous fluid communication with the cold air outlet of a vortex tube and first and second tubular nasal prongs extend from the tubular body.

In Fig. 3, the schematic of the experimental setup is shown. Nasopharygeal brain cooling was achieved by directing cooled air via a catheter in each nostril into the nasal cavities. The cold air flow rate was set by the fraction control valve of the vortex tube to the desired flow rates of 25 or 50 L/min as measured by a flowmeter (VWR Flowmeters Acrylic, FR4500 series with accuracy of ±3%, VWR International Inc). The temperature of air at the cold air outlet was monitored and recorded continuously with a thermometer (VWR digital thermometer with 0.1°C precision, VWR International Inc). A thermistor was also placed inside of one of the two nasal catheters to monitor temperature of cold air inside the nasal cavity throughout the experiments. During each cooling experiment, both brain and rectal temperatures were measured every 5 minutes.

As well, we investigate the efficiency of cooling with nasal catheter versus face mask in one pig. The inlet pressure was set at 25 PSI while the flow rate at the cold air outlet was set to 25 L/min. Baseline brain and rectal temperature were monitored for 45 to 60 minutes until they did not change for more than 0.5°C in 10 minutes, then the brain was cooled down twice first with the nasal catheters and then with a face mask with a rewarming period to baseline brain temperature between the 2 cooling periods.

3. Results

Table 1 displays a summary of the measured physiological parameters (MAP and HR) in different experiments. All monitored physiological parameters showed no significant difference during cooling. No significant changes were found with respect to Pao_2, $Paco_2$, *t*Hb, or pH. Arrhythmias were not observed during cooling.

Fig. 4 demonstrates the brain and rectal temperature profile as a function of time in method I, in which the vortex tube was supplied with compressed air from a hospital medical air outlet at fixed inlet pressure of 50 PSI. With the air flow rate of 25 L/min and temperature of −5°C ± 2°C at the cold air outlet, maximum brain-rectal temperature gradient of −2°C was reached about 45–60 minutes after the initiation of cooling. One hour post cooling, both brain and rectal temperatures decreased from 38°C and 37.4°C to 34.3°C and 35.9°C, which

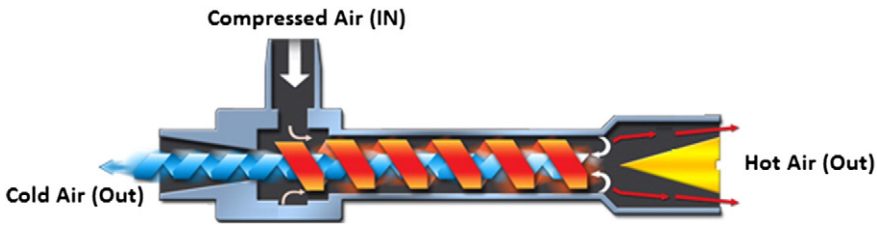

Fig. 1. Schematic diagram of the operation of a vortex tube showing the flow inlet, the cold and hot air streams, and the cold and hot outlets.