tube has 2 spiracles, 4 mm in diameter, on the tube wall. After passing through the spiracles, the cooling water, which is between the cuff and inlet tube, flows to the upper part of the cuff. During this time, the cuff wall is cooled by heat transfer between the inner cuff wall and the cooling water. Finally, in the upper part of the cuff, the cooling water flows in 2 directions and out through the outlet tubes.

2.2. Experimental apparatus and procedures

A schematic diagram of the experimental facility used in the present investigation is shown in Figure 3. The experimental apparatus includes a heater; a cooling water circulatory system, including a flow-control device; measuring equipment; and the cuff that is placed in the phantom. The cooling water circulation apparatus can adjust the temperature and quantity of cooling water flowing into the cuff. Distilled water was used as the working fluid. The running water temperature was measured with a K-type thermocouple (D = 0.3 mm) inserted into each tube. The phantom can be maintained at temperatures ranging from room temperature to 45°C, by adjusting the heater. The K-type thermocouple (D = 0.3 mm) was positioned in the phantom at 6 points (T_1 ~ T_6; positions are shown in Figure 7) between 2 places, cuff and phantom, and the phantom temperature and local surface temperature of the cuff were measured. All thermal data were fed into computers through a data logger at 1s intervals.

The phantom was maintained at the setting temperature, after the specified quantity of cold water at the desired temperature was passed through the cuff, while the output of the band heater, which was wound around the phantom circumference, was adjusted by heat transfer. In the temperature setting of the phantom, the mean values of the 2 thermocouples installed near the cuff were adjusted to the phantom temperature. The data were collected, after a steady state was achieved.

For the visualization experiment, the cuff was placed in the standing position after it was taken out of the phantom, and the observations were made. The water was mixed with insoluble fluorescent particles (d = 165 μm, ρ = 1050 kg/m^3; to trace the water dispersion) for better visualization. A specified quantity of this water was supplied, and the flow behavior was recorded with a digital video camera.

The inflow temperature ranged from T_L = 3~10°C during the experimental conditions, and the inflow, V = 100~1500 ml /min. The temperature of the phantom was maintained at

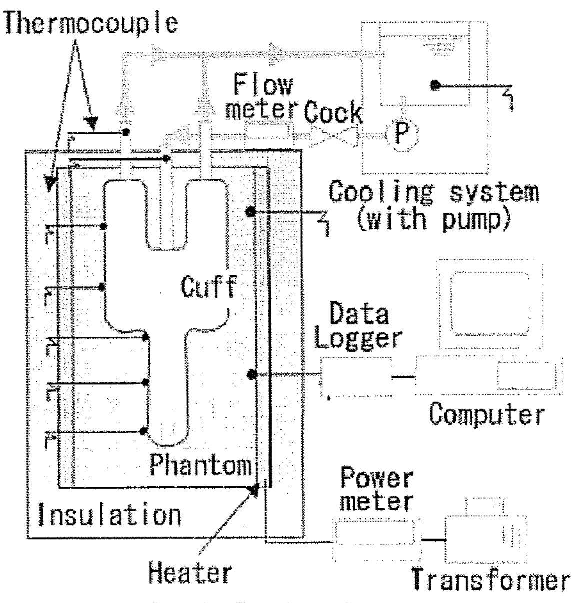


Figure 3 Experimental apparatus

T_{Pha} = 35~38°C. In addition, the measurement accuracy of this experiment was as follows. The relative temperature difference of the thermocouple was within 0.4 K. The temperature reading error was within ±2.5%, considering the accuracy of the measuring equipment. The erratic readings of the inflow were within ±0.02% of the accuracy of the flow meter.

2.3. Human body equivalent phantom

The phantom used in this experiment was a wet type one constructed with agar, boric acid, and water. The mould was removed, and the phantom was left to solidify and form a cylindrical vessel. This vessel was used for the experiment and placed in an independent (standing) position. The proportion of the components used to construct of the phantom is shown in Table 1. Furthermore, the thermal conductivity of the phantom measured by the unsteady probe technique as well as the thermal conductivity of the representative organism is shown in Table 2[10]. In the experiment, the phantom was lap coated to prevent changes in the water content due to evaporation from the exterior.

Table 1 Principal components of the phantom body

Component	Agar	Boric acid	Water
Ratio (wt%)	3.0	1.2	95.8

Table 2 Thermal conductivity

	Phantom	Ref. (10)
Thermal conductivity (W/(mK))	0.532	0.34~0.68

2.3. Calculation grid and numerical analysis method.

The GAMBIT grid generation software was used for analysis of three-dimensional CAD data from the cuff to prepare a calculation grid. The calculation grid comprised a triangular 8-faced cone grid in the cuff interior and in the vicinity of the wall. The calculation grid is shown in Figure 4 (left: coronal plane, right: median section). The calculation grid number of the cuff is shown in Table 3. In the numerical analysis, the thermo-hydrodynamic analysis software FLUENT was used.

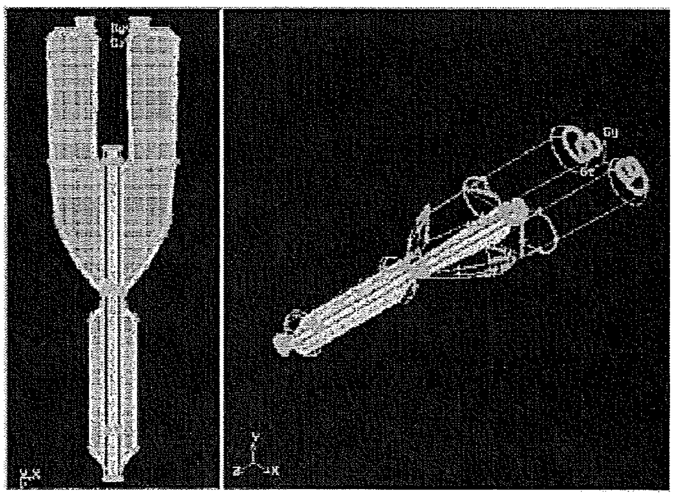


Figure 4 Numerical grid for the cuff (3D)

Table 3 Grid size of the cuff model

Cells	Faces	Nodes
803,759	1,805,366	261,420

3. Results and Discussion

3.1. Surface temperature of cuff

The relationship between surface temperature and inflow at different positions in the cuff is shown in Figure 5. The phantom temperature and inflow temperature were fixed at 37°C and 5°C, respectively. The horizontal axis of the figure indicates the thermometry position of the cuff. When the inflow is small, the cuff surface temperature is generally higher. Furthermore, no large differences in the inflow temperature were observed at the different cuff positions. However, the surface temperatures at positions 3, 5 and 6 were lower than the temperature at the other positions in the cuff. Due to these reasons, another factor was considered. At around position 3, there was an increase in the flow velocity with a rapid decrease in the water course at the cross section of the cuff center, which led to an increase in the heat transfer coefficient, thereby enhancing the cooling effect. Furthermore, near position 5, after the fluid that passed through the center of the cuff was pooled in the bifurcation, this fluid was divided between both the cuff branches; the water pools again, and the local heat transfer increases. Thus, there is increased heat transfer at position 6 due to this complicated flow, including the rotational flow, generated near the cuff exit.

3.2. Heat transfer characteristic from cuff surface

Complicated flow, including rotational flow, through the cuff facilitates heat transfer to a large extent within the cuff surface. The purpose of the cuff is to cool the biotissue in the pharynx division. Therefore, it is important to understand the heat transfer characteristics between the cooling water and cuff wall surface through which the water flows. Next, the cooling water inflow (V) and amount of heat transfer (Q) calculated from the temperature gradient (⊿T) were examined. The relationship between the cooling water inflow and

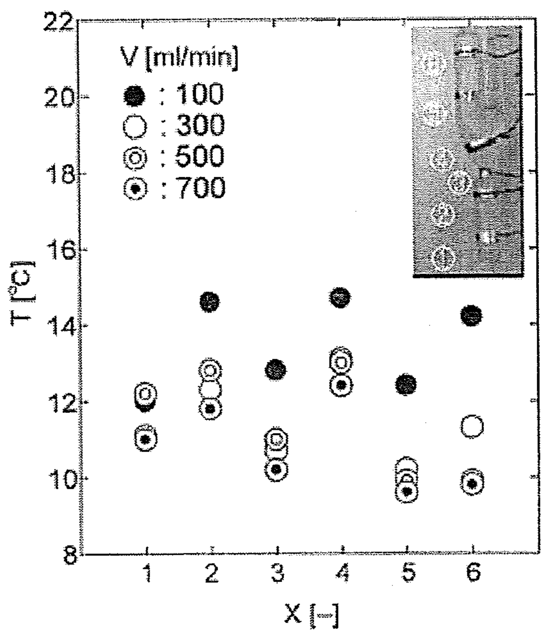


Figure 5 Temperature distribution in the cuff within the phantom

amount of heat transfer and cooling efficiency (η) of the cuff is shown in Figure 6. The cooling efficiency is calculated with the following equations.

$$\eta = \frac{T_{out} - T_{in}}{T_{Pha} - T_{in}} \times 100 \quad [\%] \qquad (1)$$

Where, T_{in}, T_{out}, and T_{Pha} are the cuff inlet temperature, outlet temperature, and phantom temperature, respectively. The phantom temperature and inflow temperature were fixed at T_{Pha} = 37°C and T_{in} = 5°C. Since the sensible heat traffic volume increases, as the inflow increases, there is a synchronous increase in the amount of heat transfer. In addition, the rapid flow, including the rotational flow, generated in the cuff due to the increased inflow is considered to be a factor inducing an increase in the amount of heat transfer. Moreover, it has been proven that the cooling efficiency exponentially decreases with an increase in the inflow. This is because the increasing temperature gradient (∠T) of the inflow decreases with increase in the inflow. In particular, the cooling efficiency stabilizes at approximately 6% at an inflow of over 750 ml/min.

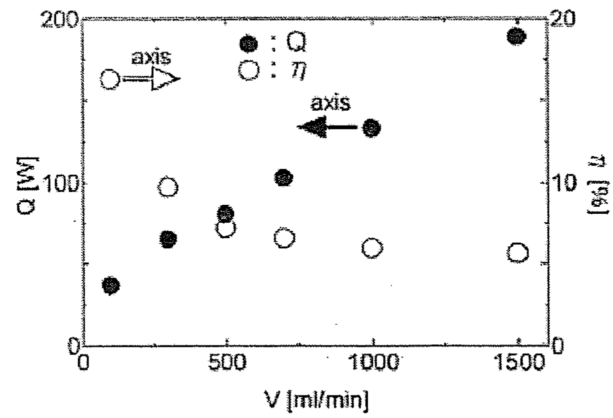
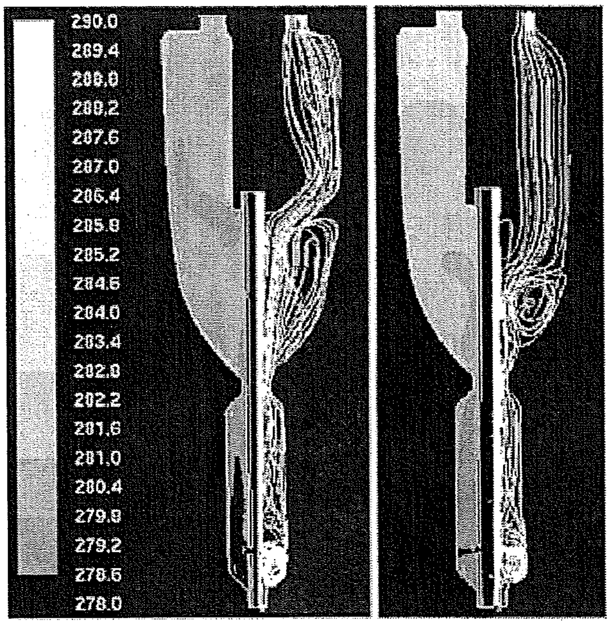


Figure 6 Relation between heat quantity and cooling efficiency

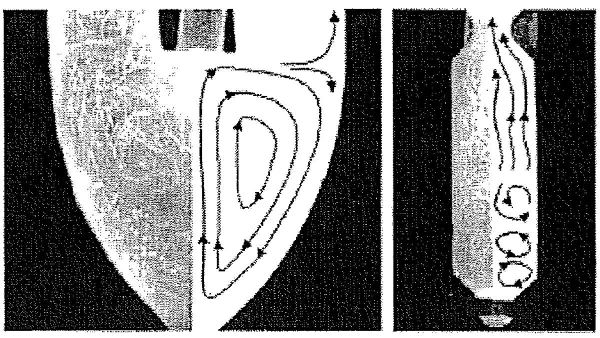
3.3. Flow characteristics in cuff

Numerical results of temperature distribution (left side) and cuff flow pattern (right side) are shown in Figure 7. (a) and (b), respectively, in the case of cooling water inflows of 500 ml/min and 150 ml/min. The inflow temperature was T_{in} = 5°C in both cases. The temperature conditions of the cuff surface during the analysis have been set as follows. On the basis of the relationship between heat quantity and cooling efficiency in Figure 6, in the boundary condition, the heat flux (q), which was divided by the cuff surface area (S = 0.021mm), was calculated in terms of the amount of heat transferred (Q). The heat flux (q) at V = 500 ml/min and 150 ml/min were 3810 W/m^2 and 2068 W/m^2, respectively. The temperature distribution in the cross section of the cuff is shown in Figure 7. In the right figure, the three-dimensional locus of the representative particles is shown in order to demonstrate the flow characteristics in the cuff in terms of the fluid particles. On the basis of the temperature distribution, we observe that the temperature at the tip and in the central section of the cuff is low. In addition, the temperature at the point whereof the fluid pools, i.e., in the area of the rotational flow, is also low. These results are in agreement with the measurement results in Figure 5. Furthermore, the temperature in the cuff in general decreases with the increase in the inflow, and there is insufficient heat exchange. Moreover, as seen in the flow pattern in Figure 8, the fluid in the cuff exhibits a rotational flow in the cuff tip, and it turns at the upper part of the cuff. It was confirmed that there is paired rotational flow at the cuff center for right and left. These flow patterns are largely affected by the change in the inflow. As shown in Figure 7, it is understood that the flow at the cuff central part is runoff without reaching the cuff surface by the rotational flow. This means that the cooling water which has been flowing from below the cuff did not contribute to the heat transfer with the cuff surface. Moreover, it is proved that the central part of the rotational flow is the stagnation point. From these points of view, it seems to be possible that the thermal efficiency increases by suppressing the rotational flow in the cuff. The images in Figure 8 (a) and (b) show the streamlined flow in each part of the cuff. Figure 8 (a) shows the central portion of the cuff and (b) shows the cuff tip. The total inflow is 300 ml/min. Figure 8 (a) shows the paired rotational flow for the right and left after the fluid pooled in the cuff bifurcation and after it was distributed in the arms. After the intense rotational flow in the cuff tip, the fluid turns centrally and flows in a rectilinear manner (Figure 8 (b)). The flow characteristics are in accordance with the numerical result shown in Figure 7.



(a) V=500ml/min (b) V=150ml/min

Figure 7 Numerical results of temperature distribution and flow patterns



(a) Middle part (b) Apical part

Figure 8 Results of the visualization experiment

4. Conclusion

The use of the pharyngeal cooling cuff for the treatment of brain hypothermia was experimentally and numerically analyzed, and this analysis led to the following conclusions.

(1) It was possible to clarify the heat- transfer characteristics of the pharyngeal cooling cuff experimentally and numeric-analytic. Furthermore, the results of this simulation result agreed with the experimental results.

(2) The cooling efficiency and amount of heat transfer in the cuff are dependent on the inflow. However, it is considered that heat transport efficiency and local heat exchange lower by the rotational flow in the cuff. The cooling efficiency stabilizes at 6%, when the inflow is greater than 750 ml/min. This is a very low value, and further improvements in the cuff are necessary. Currently we are performing both experimental and computational analysis on a cuff design which suppresses the rotational flow structure.

Acknowledgements

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Q7 NEW DEVICE 新しい手技による脳低温療法

回答：岡山大学病院・麻酔科蘇生科　武田吉正（たけだ よしまさ）

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NEW DEVICE

Q7 新しい手技による脳低温療法

回答：岡山大学病院 麻酔科蘇生科 武田吉正（たけだよしまさ）

point

- 体温のコントロールは，Central venous line cooling 法が最も優れている．
- Intranasal selective brain cooling 法は，開発中の選択的脳冷却法である．
- Pharyngeal selective cooling 法は，開発中の選択的脳冷却法である．
- 新しい脳低温療法機器には，早く冷えることと，体温のコントロールが良いことが求められている．

Q Central venous line cooling 法とは？

A 中心静脈内に留置したカテーテルを用いて血液を冷却する全身冷却法です．アメリカやヨーロッパでは医療機器として承認されていますが，2009年7月現在，日本ではまだ承認されていません．図1はAlsius社のCoolGard™を示しています．カテーテル表面にバルーン状のふくらみがあり，冷却された生理食塩水が流れます．大腿静脈から挿入する長いカテーテル（冷却用バルーン：3～4個）と，内頸静脈や鎖骨下静脈から挿入する短いカテーテル（冷却用バルーン：2個）があります．この冷却法の特徴は，比較的急速に全身冷却できることと，体温のコントロール性が良いことです．使用するカテーテルにより冷却効率は異なりますが，冷却用バルーンが3つあるカテーテルを大腿静脈から挿入した場合，膀胱温が0.8±0.3℃/hの速さで比較的速やかに低下します[1]．また，血液温を直接コントロールしているため，体温を設定通り正確に保つことができます．設定温度からの逸脱は0.24±0.14℃と報告されています[2]．復温時もゆっくりと安全に加温していくことができ，医療スタッフの労力が軽減されます．しかし，このデバイスにも欠点があります．カテーテルの外径（9.3F）がスワンガンツカテーテルのシース（7～9F）

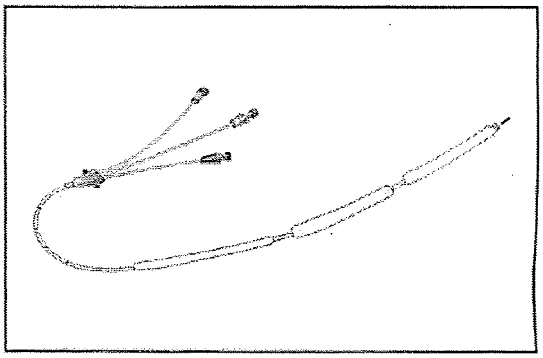

図1 Alsius社のCoolGard™
風船の中を冷生理食塩水が灌流する．
（文献1を参照して作成）

1346-0935/09/¥400/論文/JCOPY

より一回り太くなっています．そのため，刺入部に血腫を形成したり，長期留置で下肢に深部静脈血栓を形成したりする可能性があります[3]．

Q Intranasal selective brain cooling 法とは？

A 現在開発中の選択的脳冷却法です．BeneChill 社の RhinoChill システムは，揮発性の冷却液を酸素と一緒に鼻腔内に噴霧するシステムです．使用時間は 60 分で，蘇生時に脳温だけを急速に低下させることを目的としています．60 分経過後は，他の全身冷却法に移行します．現在アメリカとヨーロッパで臨床試験が行われています．スウェーデンで開発されている QuickCool は，両側の鼻腔に風船状のカフを挿入し，冷生理食塩水を灌流する方法です．冷却された静脈血が頸動脈血と熱交換し，脳温を血行性に低下させると考えられています．現在，スウェーデンとデンマークで臨床試験が行われています．

Q Pharyngeal selective cooling 法とは？

A 現在開発中の選択的脳冷却法です．厚生労働省の科学研究費により，岡山大学と大研医器株式会社が共同開発しています（図 2，i-Cool システム）．気管挿管後に風船状のカフを咽頭部に挿入し，冷生理食塩水を灌流します（図 3）．Intranasal cooling と同様に，蘇生時に脳温だけを急速に低下させることを目的にしています．使用時間は 2 時間で，その後は他の全身冷却法に移行します．咽頭の 1 cm 外側に総頸動脈が存在し，さらにその外側に内頸静脈や外頸静脈が存在します（図 4）．咽頭を冷却すると，総頸動脈が先に冷却され，血行性に脳温が低下します．アイスクリームを食べると体温が下がったように感じる（実際は脳の温度が下がっている）のと同じ原理を利用しています．血行性に冷却されるので，脳深部と脳表の温度が均一に低下します．日本国内の救命救急センター（12 施設）で，鼓膜温を観察する Randomized controlled trial が施行されています．

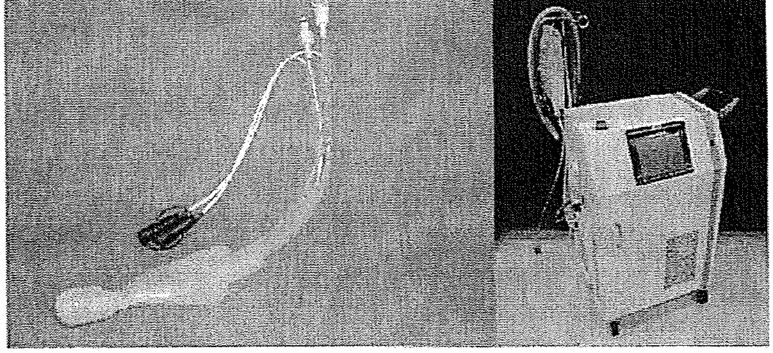

図 2　i-Cool システム
カフはラリンジアルマスクと同じ要領で挿入する．温度センサーと圧力センサーを備え，灌流装置により自動制御する．
(http://www.cc.okayama-u.ac.jp/~cool/cuff.html，http://www.cc.okayama-u.ac.jp/~cool/souchi.html より引用)

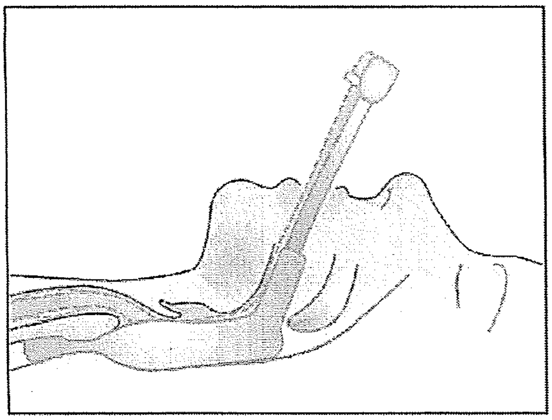

図3　咽頭冷却カフの挿入
気管挿管後，咽頭冷却カフを挿入する．
(http://www.cc.okayama-u.ac.jp/~cool/intou.html より引用)

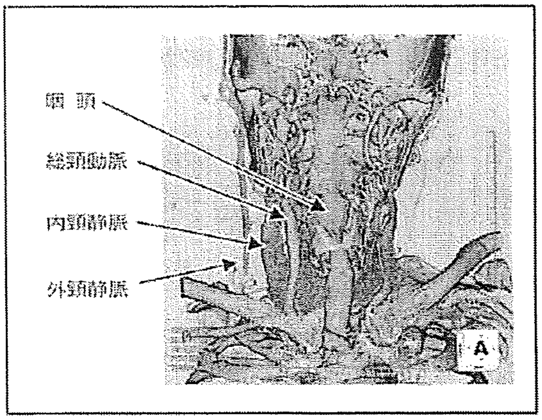

図4　頸部3D-CT
咽頭の1cm外側に総頸動脈が存在し，さらにその外側に内頸静脈や外頸静脈が存在する．咽頭側から冷却すると総頸動脈が先に冷却され脳温が低下する．

Q 使い方のポイントは？

A いかに優秀な機械を使用しても，患者が寒冷反応でシバリングを呈すると，速やかな体温低下は望めません．患者の状態を観察しながら，十分な麻酔深度を維持することがポイントです．以下の投与量を目安に，鎮静薬と麻薬の初期投与を開始します．

鎮静薬：ミダゾラム　0.2 mg/kg/h
麻　薬：フェンタニル　2 μg/kg/h

麻酔深度を調節してもシバリングの発生を抑制できない場合は，筋弛緩薬の投与を考慮します．ドロペリドールを投与すると，末梢血管が拡張し，体温低下が促進されます．メジャートランキライザーは緩徐に投与し，輸液を負荷して末梢血管拡張に対応する必要があります．

Q 機器を用いて治療を成功させるための秘訣（コツ）は？

A 復温を1日程度かけてゆっくり行います．急速に復温すると，末梢循環不全による重度のアシドーシスや凝固障害など，重篤な合併症を併発することがあります．

Q ここだけは気をつけたいピットフォールは？

A 全身冷却を施行すると，電解質異常(特に低カリウム血症，低リン血症）や血小板減少，凝固障害を呈します．これらを定期的に測定します．また，低体温により肺炎

を合併しやすくなります．口腔内の洗浄，体位変換，栄養管理等，人工呼吸器関連肺炎の予防を徹底します．

Q 適応は？

A 脳低温療法の有効性が Randomized controlled trial で示されているのは，心停止蘇生後脳障害[4]と新生児の低酸素性虚血性脳症(hypoxic ischemic encephalopathy)[5]です．頭蓋内圧が亢進している頭部外傷患者に対し脳低温療法は有効ですが，すべての頭部外傷患者に脳低温療法の適応があるわけではありません[6]．脳梗塞に脳低温療法が有効であることは，多くの動物実験で観察されています．しかし，臨床研究がほとんど行われていないため，臨床での有効性は確認されていません．今後の研究が必要です．

Q タイミングは？

A 心停止蘇生後の脳低温療法は，早期に脳温を低下させるほど有効です．脳低温療法の有効性を示す臨床研究は，2例行われています．ヨーロッパで行われた臨床研究では，心拍再開 105 分後より冷却を開始し，冷却開始 6 時間後に目標温（32～34℃）に到達しています．オーストラリアで行われた臨床研究では，心拍再開直後より冷却を開始し，冷却開始 2 時間後に目標温（33℃）に到達しています．以上より，少なくとも蘇生成功 105 分後から 6 時間かけて冷却しても有効だといえます．早期に体温を低下させるため，心拍再開後に冷輸液を急速静注する方法も試みられています[7]．

Intranasal selective brain cooling 法や Pharyngeal selective cooling 法は，選択的脳冷却法なので，心拍再開前（蘇生時）から施行します．

Q 今後の展望は？

A 今後の脳低温療法の手技や機械の開発は，以下の 2 点を目標に進められていくと考えられます．

1）早く脳温を低下させる．

2）体温を設定温に正確にコントロールする．

人の体重はおよそ 50 kg ありますが，脳はわずか 1.4 kg しかありません．50 kg の肉体の温度を低下させるのは大変ですが，1.4 kg の脳の温度を低下させることは簡単です．そのため，早期に脳温を低下させるには，選択的脳冷却法（Intranasal selective brain cooling 法や Pharyngeal selective cooling 法）が適した冷却法であるといえます．体温のコントロールには，Central venous line cooling 法が最も優れていると思われます[2]．

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the brain is protected against damage. For the purpose of treatment, brain hypothermia is divided into mild hypothermia (core temperature, 34°C) and moderate hypothermia (32°C). The temperature of the brain is lowered and maintained at low temperatures by lowering the body temperature. The latter is achieved by covering the whole body with a water-cooled blanket. In this method, the patient's body is wrapped with a water-cooled blanket, and cold water (approximately 20°C) is circulated through the blanket. It is also possible to simultaneously maintain the brain temperature at the desired degree and strictly monitor the temperature. However, this management strategy, i.e., conventional hypothermia treatment, requires a great deal of time to bring about changes in body temperature and for acute state transition of the pathology. Therefore, research and development on medical instruments such as water-cooling blankets, headgear, and mufflers for the purpose of cooling of body parts and lowering the brain temperature are widely being conducted[6].

Takeda et al.[7]~[8] developed the pharyngeal cooling cuff by analyzing the anatomy of the pharynx division. This cuff is inserted through the oral cavity of the patient, and it can cool the common carotid artery, which is located approximately 10 mm outside the pharynx division. Thus, cooling and temperature control of the brain is possible via the cooling of the main blood vessel that supplies the brain. In comparison with conventional whole-body cooling, the pharyngeal cuff method rapidly lowers the brain temperature. Moreover, the countermeasures of acute brain temperature management and early brain cooling during life-threatening emergencies related to brain diseases are possible with the latter method. For acute phase of brain cooling, we assume that physiological saline at 5°C should be used to cool the cuff. During animal testing[9], this cuff has been shown to produce a good cooling effect on the brain. However, the optimum cooling efficiency of this cuff has not been determined since the structure of this device is based on the pharynx shape.

On the basis of this background, we aimed to understand the flow and heat transfer characteristics of the pharyngeal cooling cuff. In this report, in order to evaluate pharyngeal cooling, we analyzed the heat transfer between the cuff and a phantom body (hereafter referred to as phantom), which was considered to be equivalent to the human body. In particular, we focused on the thermal transport characteristics within the cuff. Further, computational fluid dynamics (CFD) analysis was carried out to analyze the flow in the cuff, and the cooling efficiency was examined under various conditions. These results are useful as they provide the basic information required to develop the clinical applications of the cuff and to improve the cuff to ensure better cooling of the pharynx. Future studies will address transport within the surrounding tissue and the effectiveness of carotid artery blood cooling.

Nomenclature

D	:	Diameter
L	:	Length
Q	:	Heat quantity
q	:	Heat flux
S	:	Surface area
T	:	Temperature
ΔT	:	Temperature difference t
U	:	Velocity
V	:	Inlet flow
X	:	Local position
η	:	Cooling efficiency
ρ	:	Density