Integration of jugular venous return and circle of Willis in a theoretical human model of selective brain cooling

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Neimark MA, Konstas A-A, Laine AF, Pile-Spellman J. Integration of jugular venous return and circle of Willis in a theoretical human model of selective brain cooling. J Appl Physiol 103: 1837–1847, 2007. First published August 30, 2007; doi:10.1152/japplphysiol.00542.2007.—A three-dimensional mathematical model was developed to examine the induction of selective brain cooling (SBC) in the human brain by intracarotid cold (2.8°C) saline infusion (ICSI) at 30 ml/min. The Pennes bioheat equation was used to propagate brain temperature. The effect of cooled jugular venous return was investigated, along with the effect of the circle of Willis (CoW) on the intracerebral temperature distribution. The complete CoW, missing A1 variant (mA1), and fetal P1 variant (fP1) were simulated. ICSI induced moderate hypothermia (defined as 32–34°C) in the internal carotid artery (ICA) territory within 5 min. Incorporation of the complete CoW resulted in a similar level of hypothermia in the ICA territory. In addition, the anterior communicating artery and ipsilateral posterior communicating artery distributing cool blood to the contralateral anterior and ipsilateral posterior territories, respectively, imparting mild hypothermia (35 and 35.5°C) respectively. The mA1 and fP1 variants allowed for sufficient cooling of the middle cerebral territory (30–32°C). The simulations suggest that ICSI is feasible and may be the fastest method of inducing hypothermia. Moreover, the effect of convective heat transfer via the complete CoW and its variants underlies the important role of CoW anatomy in intracerebral temperature distributions during SBC.

intracarotid saline infusion; intracerebral vascular flow rates; therapeutic hypothermia

Therapeutic hypothermia has been repeatedly shown to be effective in limiting central nervous system damage in animal models and clinical studies of ischemic stroke and cardiac arrest (6, 24). In most clinical studies, hypothermia is induced by surface cooling. Although this is the simplest and most cost-effective method of inducing hypothermia (13), it has two major limitations. First, surface cooling requires 3–7 h to reach the target brain temperature of 32–34°C (27, 41), although endovascular whole body cooling may be able to accelerate the induction of hypothermia (18). Second, whole body cooling methods are associated with several adverse effects such as impaired immune function, decreased cardiac output, pneumonia, and cardiac arrhythmias (13). Selective brain cooling (SBC) may be able to address both limitations of whole body cooling.

Different methods for SBC exist (21). The noninvasive methods most commonly used are cooling caps and helmets. However, theoretical analyses (8, 38, 46) and empirical measurements (7, 36, 51, 56) suggest that they are only effective in reducing the temperature in superficial cerebral regions and not deep brain structures. One potential method of SBC is intracarotid cold saline infusion (ICSI) in which cold saline is infused into the internal carotid artery (ICA) via transfemoral catheterization. This method is potentially much faster than whole body cooling and more effective than surface SBC. A recent theoretical study addressed the clinical feasibility of ICSI for inducing hypothermia (32). The theoretical analysis suggested that an infusion rate of 30 ml/min is sufficient to induce moderate hypothermia (defined as 32–34°C) within 10 min in the ipsilateral hemisphere. The theoretical model employed in this study, however, did not consider cooled jugular venous blood return to the body core, which should result in whole body temperature changes.

All the previous published theoretical analyses assume that blood from a particular feeding artery perfuses only a particular region in the brain, without mixing from the other source arteries (8, 32, 38). In reality, mixing of blood from different afferent vessels occurs within the circle of Willis (CoW). Blood can potentially flow from one hemisphere to another through the anterior communicating artery (ACoA) and from the ICA to the posterior cerebral artery (PCA) through the posterior communicating artery (PCoA). Intracerebral convective heat transfer through the CoW may affect the temperature response during ICSI. Furthermore, common variations in CoW anatomy exist such as a fetal P1 segment (fP1) of the PCA and a missing A1 segment (mA1) of the anterior cerebral artery (ACA) (37). Intracerebral temperature response may be different in these CoW variants (5).

The hypothesis of this study is that ICSI can selectively cool areas of the human brain and that spatiotemporal patterns of cooling will be affected by CoW anatomy and venous return. Our aim is thus to address three questions concerning the intracerebral temperature response to ICSI. First, what is the effect of jugular venous return on core temperature, and does a lower core temperature reinforce the induction of SBC? Second, how will redistribution of cooled ipsilateral ICA blood by the CoW affect the temperature response of the brain? Third, will variations in the CoW affect intracerebral temperature distributions? The impact of SBC on the distribution of cerebral blood flow (CBF) in the CoW is also examined.

Glossary

Abbreviations

ACA Anterior cerebral artery
ACoA Anterior communicating artery
BA Basilar artery
CoW Circle of Willis
fP1 Fetal P1 segment of posterior cerebral artery
ICA Internal carotid artery
Hct Hematocrit

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be 2.8°C for a saline flow rate of 30 ml/min (32).

For brain tissue, metabolism is a function of temperature and perfusion

\[ q = q_0 \cdot 3.0^{0.084(T - 37)} \]  
\[ \omega = \omega_0 \cdot 3.0^{0.084(T - 37)}(1 - 2.2\Delta_{tc}) \]

The coefficients in Eqs. 3 and 4 were derived by fitting data points from PubMed-indexed experimental studies, reviewed elsewhere (32).

The root mean square error between the data points and the function was minimized by varying the coefficients through the unconstrained nonlinear optimization.

ICSI limited the amount of intracarotid blood flow in Eq. 2 according to

\[ ICA \text{ Blood Flow} = ICA \text{ Total Flow} - \text{Saline Flow} \]
Effect of infusion volume on hematocrit. When the bloodstream is infused with isotonic saline, part of it enters the extravascular space and part of it is removed by the kidneys. The remaining volume of saline hemodilutes the blood. An expression for the resulting change of hematocrit is given as follows (32):

\[
\Delta \text{Hct} = \frac{\delta V_{\text{RBC}} \Delta V_{\text{IV}}}{V_{\text{IV0}}(V_{\text{IV0}} + \delta \Delta V_{\text{IV}})}
\] (6)

where \(V_{\text{RBC}}\) is the total red blood cell volume, \(V_{\text{IV0}}\) is the initial total intravascular volume (including \(V_{\text{RBC}}\)), \(\Delta V_{\text{IV}}\) is the volume of added saline, and \(\delta\) is the fraction of infused water that remains intravascular (i.e., does not end up in the extravascular space and is not removed by the kidneys). An initial hematocrit of 42% and an initial \(V_{\text{IV0}} = 5.0\) liters is assumed (implying \(V_{\text{RBC}} = 2.1\) liters).

\(\delta = 0.42\) was determined in a previous study (32) by fitting Eq. 6 by unconstrained nonlinear optimization with published experimental hypervolemic hemodilution data (19, 20, 26, 28, 45, 52, 53).

For the territory of the brain perfused by the ipsilateral ICA, the values of hematocrit (which affects perfusion) had to be modified because of the cold saline infusion. An expression for the local dilution effect of the infusion is given by

\[
\text{Hct}_{\text{local}} = \frac{\text{ICA Blood Flow} \cdot \text{Hct}}{\text{ICA Blood Flow} + \text{Saline Flow}}
\] (7)

Incorporation of venous return. Since blood and brain tissues achieve thermal equilibrium (2), venous return temperatures were calculated by integrating the product of the brain temperature and blood perfusion over the entire brain model as follows (14):

\[
T_{\text{venous}} = \int \int \int \omega(\vec{r}) T(\vec{r}) d\vec{r}
\] (8)

\(T_{\text{venous}}\) is the average venous return temperature. Equilibration of venous blood with the body core temperature (\(T_{\text{core}}\)) will decrease \(T_{\text{core}}\) (54):

Table 1. Physical and physiological properties in the model (modified from Ref. 32)

<table>
<thead>
<tr>
<th>Anatomic Structure of the Head</th>
<th>Specific Heat (c), J/kg K</th>
<th>Mass Density (\rho), kg/m³</th>
<th>Thermal Conductivity (k), W/m K</th>
<th>Perfusion (\omega_0), ml/(min · 100 g)</th>
<th>Metabolic Rate (q_0), W/m³</th>
<th>Radius (r), mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saline</td>
<td>4,213</td>
<td>1,006</td>
<td>0.5</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Blood</td>
<td>3,800</td>
<td>1,050</td>
<td>0.5</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Scalp</td>
<td>4,000</td>
<td>1,000</td>
<td>0.342</td>
<td>2.0</td>
<td>363.4</td>
<td>93</td>
</tr>
<tr>
<td>Bone</td>
<td>2,300</td>
<td>1,520</td>
<td>1.16</td>
<td>1.8</td>
<td>368.3</td>
<td>89</td>
</tr>
<tr>
<td>Gray matter</td>
<td>3,700</td>
<td>1,030</td>
<td>0.49</td>
<td>80</td>
<td>16,700</td>
<td>85</td>
</tr>
<tr>
<td>Whitematter</td>
<td>3,700</td>
<td>1,030</td>
<td>0.49</td>
<td>20</td>
<td>4175</td>
<td>67</td>
</tr>
</tbody>
</table>

N/A, not applicable.
where $m_{\text{body}} = 70$ kg is body mass and $c_{\text{body}} = 3.475$ J·kg$^{-1}·K^{-1}$. In this study, the body core is modeled as a compartment separate from the brain with uniform temperature that is affected only by the blood temperature returning from the brain model. See also DISCUSSION.

**CoW model.** Representative values averaged from published human data of CoW vessels were used to simulate individual vessels in the present CoW model (12, 37, 47). Representative values for vessels in complete CoW, as well as vessels in CoW with mA1 segment of ACA or fP1 segment of PCA are summarized in Table 2. Modeling of the CoW was performed with a linear manner, the CoW afferent vessels act as flow sources and pressures at the origins of the ICAs and BA were clamped to mean arterial pressure. The set of Kirchoff’s law equations is expressed by the following matrix equation, which was used to determine the pressure values $P_i$:

$$ F = G(P_2 - P_1) $$

(10)

The conductance values in this equation were calculated according to Eq. 11. Subscripted numbers represent points along the CoW (Fig. 1C) and the vessels between them (double digits). MAP = 95 mmHg is mean arterial pressure. $G_{\text{ACA}}$ is the conductance of the ICA and $G_{\text{BA}}$ is the combined conductance of the vertebral and basilar arteries.

$$ G = \frac{\pi D^4}{128 \eta_{\text{blood}} L} $$

(11)

where $\eta_{\text{blood}}$ is blood viscosity, $L$ is vessel length, and $D$ is vessel diameter. The hemispheric model was divided up into six perfusion territories corresponding to each of the cerebral arteries (Fig. 1, A–C). These vascular territories were chosen to correspond roughly to both perfusion regions recently reported in selective arterial spin labeling perfusion studies (48) and cerebral artery blood flow proportions described in various studies (11, 12, 47). Flow rates through the CoW afferent arteries were determined by integrating the $\omega$ values in the corresponding perfusion territories in Fig. 1, A and B (and calculated using Eq. 4) according to

$$ F = \int \int \omega dV $$

(12)

Blood flows in the CoW and supply vessels (i.e., ICAs and BA) were determined by Kirchoff’s circuit laws, which state that the sum of incoming flows toward an arterial junction is zero and the sum of pressure changes in a closed arterial circuit is zero. In this manner, the CoW afferent vessels act as flow sources and pressures at the origins of the ICAs and BA were clamped to mean arterial pressure. The set of Kirchoff’s law equations is expressed by the following matrix equation, which was used to determine the pressure values $P_i$:

$$ [P_i] = \begin{bmatrix} F_{\text{ACA}} \\ F_{\text{BA}} \\ F_{\text{PCA}} \\ F_{\text{ICA}} \end{bmatrix} $$

(13)

After solving for all the $P_i$ values of the CoW, flow values in all the CoW and source vessels were calculated according to Eq. 10. The combination of flows in the CoW allowed the calculation of temperature and hematocrit for each of the vessels in the model. For every junction of vessels, Eq. 10 was used to determine which vessels had flows entering.

### Table 2. Length and diameters of vessels in complete CoW, mA1, and fP1 models (averaged from Refs. 12, 37, 47)

<table>
<thead>
<tr>
<th>(mm)</th>
<th>ICA</th>
<th>BA</th>
<th>VA</th>
<th>iA1</th>
<th>cA1</th>
<th>ACoA</th>
<th>iP1</th>
<th>cP1</th>
<th>iPCoA</th>
<th>cPCoA</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L$</td>
<td>225</td>
<td>30</td>
<td>225</td>
<td>13.8</td>
<td>13.8</td>
<td>2.7</td>
<td>7.2</td>
<td>7.2</td>
<td>13.3</td>
<td>13.3</td>
</tr>
<tr>
<td>$D_{\text{complete}}$</td>
<td>3.57</td>
<td>3.24</td>
<td>2.71</td>
<td>1.95</td>
<td>1.95</td>
<td>1.40</td>
<td>1.82</td>
<td>1.82</td>
<td>1.14</td>
<td>1.14</td>
</tr>
<tr>
<td>$D_{\text{mA1}}$</td>
<td>3.57</td>
<td>3.24</td>
<td>2.71</td>
<td>0.16</td>
<td>2.33</td>
<td>2.33</td>
<td>1.79</td>
<td>2.14</td>
<td>1.74</td>
<td>1.66</td>
</tr>
<tr>
<td>$D_{\text{fP1}}$</td>
<td>3.57</td>
<td>3.24</td>
<td>2.71</td>
<td>1.99</td>
<td>2.30</td>
<td>1.63</td>
<td>1.30</td>
<td>2.61</td>
<td>2.01</td>
<td>2.08</td>
</tr>
</tbody>
</table>

$L$, vessel length; $D_{\text{complete}}$, vessel diameter in complete CoW; $D_{\text{mA1}}$, vessel diameter in CoW with mA1; $D_{\text{fP1}}$, vessel diameter in CoW with fP1; the letters i and c prior to the vessel abbreviation represent ipsilateral and contralateral sides of the CoW.

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Temperature in each of the CoW vessels was determined by using the temperatures of the source vessels (i.e., ICAs and BA), acquired from Eqs. 2 and 9. Ultimately, the temperature of each CoW efferent (i.e., ACA, MCA, PCA) was calculated by using Eq. 14 and was used as the arterial temperature in Eq. 1 to propagate the brain temperature. This temperature was also used in Eqs. 3 and 4 to determine brain perfusion and metabolism for Eq. 1. Similarly, hematocrit of each of the source vessels was determined by using Eqs. 6 and 7. Hematocrit in the remaining CoW vessels and CoW efferents was determined with Eq. 15. Hematocrit values from CoW efferents were used in Eq. 4 to determine blood flow for the corresponding territories.

Blood viscosity was dependent on the temperature, hematocrit, and shear rate (SR) (10):

$$\eta_{\text{blood}} = \left(9.21 e^{0.0137 \cdot \text{Hct}}\right) \left[1.74 + \frac{9.78}{1 + e^{1.38(T - 15.2)}}\right]$$

where

$$SR = \frac{32F}{\pi D^2}$$

At every iterative step, the vascular resistance of each vessel was recalculated according to Eq. 16 and Eq. 11. The resistive matrix in Eq. 13 was also reevaluated to determine pressures and flows in the CoW.

Shear rate, a function of blood velocity and vessel diameter, was determined (23) according to

$$SR = \frac{32F}{\pi D^2}$$

Figure 1D shows a flowchart demonstrating relationships between all model components and parameters. Simulations were performed in MATLAB by using the same grid spacing, temporal spacing, and overall numerical procedure as from a previous study (32).

RESULTS

**Effect of ICSI in the venous return model.** Figure 2 examines the effect of ICSI at a rate of 30 ml/min on the transient temperature profile of a human brain model incorporating jugular venous return. There was a two-phase decrease in ipsilateral ICA territory temperature. The initial fast phase cooled the ICA territory temperature to therapeutic levels (34°C) in ∼5 min. The sustained phase of cooling resulted in a slower continuous cooling of the ipsilateral ICA territory, reaching a minimum temperature of 31.1 ± 0.0148°C after 60 min of ICSI blood flow rate (not including 30 ml/min infusion) (Fig. 3). Systemic hematocrit decreased from 42 to 37.5% over the course of the infusion whereas local hematocrit decreased from 37 to 31%. Figure 4A illustrates the spatial temperature distribution after 60 min of ICSI in the venous return model. Inclusion of jugular venous return had a mild cooling effect in the rest of the brain. Body temperature fell by ∼1°C after 1 h of infusion. In Fig. 6, body temperature from the venous return ICSI model is compared with a similar 30 ml/min venous infusion model of 2.8°C saline. Body temperature in the two models is similar although the venous return ICSI temperature is slightly higher. This temperature difference is reflected in lower brain temperatures observed in the ICSI model.

**CoW model: baseline flow rates.** Table 3 shows flow rates for the ipsilateral ICA, contralateral ICA, and basilar artery (BA) at baseline (i.e., before cold saline infusion) for three separate models: The complete CoW, mA1 CoW, and fP1 CoW. The baseline flow rate values are compared with values from three other studies. Two of these studies utilized phase contrast magnetic resonance angiography to obtain in vivo flow rates from subjects, and one study employed a nonlinear vascular flow model. The baseline flow rates in the feeding arteries of the present model were within the range of values reported in the literature.
Complete CoW model: effect of ICSI on brain temperature and CBF distribution. The transient temperature profile of the ICA territory in the model incorporating the jugular venous return and complete CoW model was similar to that for the venous return model without the CoW. However, the spatial temperature distribution maps reveal two differences between the two models (Fig. 4, A and B). First, the ipsilateral ICA territory was cooled less in the complete CoW, though it remained well within the potentially therapeutic temperature range. Second, the temperatures of the ipsilateral PCA territory and the contralateral ACA territory were mildly hypothermic (≤35.5°C). No appreciable cooling below body core temperature was achieved in the corresponding territories of the jugular venous return model.

For the complete CoW, the afferent blood supply was split symmetrically between the ipsilateral and contralateral afferent arteries with the ICAs supplying 3.5 times as much blood as the BA at the onset of ICSI and 3.2 times after 1 h of ICSI. Before infusion of cold saline, there was no blood flow through the ACoA and only a small flow through the PCoAs (Fig. 5A). Also, the ICAs contributed to the blood supply of the PCA territories since the direction of flow through the PCoAs was from anterior to posterior. ICSI resulted in an asymmetrical afferent blood supply. Total flow was reduced more in the ipsilateral ICA than the contralateral ICA (225 vs. 250 ml/min). Another notable observation was that ICSI caused a 20 ml/min ipsilateral-to-contralateral flow through the ACoA.

CoW with a mA1 segment of ACA: effect of ICSI on brain temperature and CBF distribution. The main difference between the model with a mA1 segment of ACA and the complete CoW model was the diameter of A1. The mA1 had a diameter of 0.16 mm compared with the usual A1 diameter of 1.95 mm in the complete CoW model (Table 2). In subjects with a mA1 segment, the missing segment may be either ipsilateral or contralateral to the infused ICA. Compared with the complete CoW model, ICSI in the same side as the mA1 segment (ipsilateral mA1 model) resulted in a deeper level of hypothermia in the ipsilateral middle cerebral artery (MCA) territory (30.5 vs. 32°C) and an induction of therapeutic-level hypothermia in the ipsilateral PCA territory (Fig. 4C). However, the ipsilateral ACA territory was not cooled. There was an asymmetrical blood supply in the steady-state ipsilateral mA1 model. The ipsilateral mA1 had effectively no blood flow, whereas blood flow was almost doubled in the contralateral A1 segment compared with the contralateral A1 in the complete CoW model (Fig. 5B). Ipsilateral ICA blood flow was 30% less than contralateral ICA flow, and a significant proportion of the contralateral ICA flow was directed to the ipsilateral ACA via the ACoA.

ICSI to the opposite side from the mA1 segment (contralateral mA1 model) produced a markedly different distribution of hypothermic temperatures in the brain. A uniform level of cooling (32.5°C) was achieved in the contralateral ACA, ipsilateral ACA, and ipsilateral MCA territories (Fig. 4D). The ipsilateral PCA territory did not cool. Cooled ipsilateral ICA blood was directed to the ipsilateral ACA and the contralateral ACA via the ipsilateral A1 segment and the ACoA, leading to hypothermia in the ipsilateral ACA and contralateral ACA territories. The direction of blood flow in the ipsilateral PCoA was from posterior to anterior (Fig. 5C).

<table>
<thead>
<tr>
<th>Table 3. Comparison of CoW feeding vessel flow rates between the present model and published data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complete CoW</td>
</tr>
<tr>
<td>--------------</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Tanaka et al (47)</td>
</tr>
<tr>
<td>Hendriks et al. (21a)</td>
</tr>
<tr>
<td>Moore et al. (37)</td>
</tr>
<tr>
<td>Current model</td>
</tr>
</tbody>
</table>

Values for experimental studies are given as means ± SD. *Ipsilateral and contralateral values were averaged.

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CoW with a fP1 segment of PCA: effect of ICSI on brain temperature and CBF distribution. The main difference between the model with a fP1 segment of PCA and the complete CoW model was the diameter of P1. The fP1 had a diameter of 1.30 mm compared with the usual P1 diameter of 1.82 mm in the complete CoW model (Table 2). In subjects with a fP1 segment, the hypoplastic vessel may be ipsilateral (ipsilateral fP1 model) or contralateral (contralateral fP1 model) to the infused hemisphere. The ipsilateral ICA territory reached a similar level of hypothermia after ICSI in the ipsilateral fP1 model as in the complete CoW model. However, the ipsilateral PCA territory reached lower hypothermic temperatures in the ipsilateral fP1 model than in the complete CoW model. In the present study, perfusate temperature and brain temperature in the ICA territory continued to decrease even after the initial fast phase of cooling was completed. This is in contrast to a previous theoretical study of ICSI (32) where venous return was omitted from the model. In this previous study ipsilateral ICA territory temperature demonstrated a similar initial fast cooling phase but then started gradually increasing after the end of the fast phase. Similarly, at the point at which the ICA and perfusion temperatures began increasing, the ICA flow rate also began increasing. This was explained by hemodilution. In the present study, which accounted for core body cooling by venous return, the ICA flow rate leveled off at 37°C as in the nonvenous return model (32) but continuously changes according to cooled venous blood that returns from the brain. Second, intracerebral convective heat transfer through the CoW is modeled and its effect on brain temperature distribution in the human brain is examined. Previously published heat transfer models attribute intracranial heat transfer to conduction only (8, 32, 38, 44, 54, 55). Third, two common CoW variants are simulated and their role in intracerebral temperature distribution is examined. The model also allows for an analysis of the impact of SBC on the CBF distribution in the CoW. Baseline flow rates for the CoW model for the complete CoW and two variant types compared with three other studies strongly suggest the model’s ability to accurately represent arterial flow rates.

**Comparison of venous return model to nonvenous return model.** In the present study, perfusate temperature and brain temperature in the ICA territory continued to decrease even after the initial fast phase of cooling was completed. This is in contrast to a previous theoretical study of ICSI (32) where venous return was omitted from the model. In this previous study ipsilateral ICA territory temperature demonstrated a similar initial fast cooling phase but then started gradually increasing after the end of the fast phase. Similarly, at the point at which the ICA and perfusion temperatures began increasing, the ICA flow rate also began increasing. This was explained by hemodilution. In the present study, which accounted for core body cooling by venous return, the ICA flow rate leveled off (Fig. 3), indicating that the effect hemodilution, which increases blood flow, was counteracted by the effect of lower brain temperatures according to Eq. 4.

**CoW blood flows and cooling patterns.** There was a wide variation of spatiotemporal cooling patterns based on which CoW variant was modeled. For the complete CoW, mild hypothermia (35°C) was observed in the contralateral territory of the ACA. This can be explained by the both the ipsilateral-to-contralateral cold flow through the ACoA and the resulting
reduced flow of warm blood through the contralateral A1 segment (Fig. 4B). For the CoW with a missing A1 segment ipsilateral to ICSI, the territory of the ipsilateral ACA was not cooled at all because the cooled perfusate through the ipsilateral ICA could not be communicated to the ipsilateral ACA, and therefore this vessel received its entire blood supply from the warm contralateral side. Because all the cooled perfusate was transmitted to the ipsilateral MCA and PCA territories, these regions cooled more than in the complete CoW case. For the contralateral fetal P1 CoW, there was greater cooling in the contralateral ACA territory than in the complete CoW case (34 vs. 35°C). However, the ipsilateral PCA territory did not cool at all. These results can be explained by the high resistance of the contralateral P1 diverting flow from the BA to the ipsilateral side and causing a posterior-to-anterior flow through the ipsilateral PCoA ensuring that the ipsilateral PCA region would not be cooled. This in turn caused a greater ipsilateral-to-contralateral flow through the ACtA, cooling the contralateral ACA region.

Implications of the results. The results of the present study have several physiological and clinical implications. Cooled jugular venous return influenced SBC by reducing the temperature of the ipsilateral ICA territory and each of the other territories by an additional 1°C after 60 min of ICSI. The additional brain temperature decrease reflected the corresponding body core temperature drop. The mild core cooling facilitated SBC, yet body temperatures never reached levels at which adverse effects of whole body hypothermia occur (13). Indeed, mild systemic hypothermia as observed in our study is not entirely unwanted because it could help maintain SBC at lower cold saline infusion rates after target temperature is reached without imparting aforementioned deleterious side effects of systemic hypothermia.

The complete CoW allowed for interhemispheric and ipsilateral ICA-to-PCA convective transfer of the cooled ipsilateral ICA blood, mildly cooling the contralateral ACA and ipsilateral PCA territories. The mA1 and fP1, two common CoW variants, allowed for sufficient cooling of the ipsilateral MCA territory but produced very different results regarding the ipsilateral ACA, contralateral ACA, and ipsilateral PCA territory temperatures, depending on the anatomical variant and its relation to the site of ICSI. The influence of the convective heat transfer via the complete CoW and its variants underlies the importance of including it in hypo- and hyperthermic brain models. It also suggests that in animal experiments of brain cooling, temperature recordings should be obtained from all major perfusion territories and not just from one or two, as has been done in the past (9, 42).

The model predicts that therapeutic hypothermic levels can be potentially achieved after 5–10 min of ICSI. This would be 18 to 84 times faster than the 3–7 h needed for whole body cooling through noninvasive methods (27, 41) and 10 to 30 times faster than whole body endovascular cooling (18). Furthermore, the failure of noninvasive SBC methods in inducing hypothermia (7, 36, 51) makes ICSI the only potential method of rapidly inducing hypothermia. It is well established that the therapeutic window, i.e., the time period in which ischemic stroke can be treated, is around 3 h (31). Hence, ICSI has important clinical implications as it is the only potential method of hypothermia induction with the ability to cool the ipsilateral brain fast enough so as to not miss the therapeutic window. Furthermore, rapid induction of hypothermia with ICSI may lengthen the therapeutic window and allow a combination with techniques that aim at restoring the blood circulation, like local intra-arterial thrombolysis or mechanical thrombectomy. Other drugs commonly used to manage secondary complications of ischemic stroke could be infused through the catheter administering ICSI (43). The model suggests that there are significant blood flow changes in the CoW after inducing hypothermia and changes in flow distributions occur with variations in the CoW anatomy. The derived blood flow values for each CoW vessel may allow for adjustments in the doses of drugs coadministered with ICSI according to the each subject’s CoW anatomy.

The present model predicts that 60 min of ICSI at 30 ml/min decreases the local hematocrit to 30.6%. Extensive experience with cardiopulmonary bypass operations established hematocrit values in the very low 20s as the lowest acceptable levels in terms of safety (35). From a clinical applicability point of view, the theoretical maximum safe duration of hypothermia maintenance with ICSI can be up to 3 h, since, by extrapolating the local hematocrit curve in Fig. 3, the model suggests it takes around 3 h to reach hematocrit values in the low 20s. Postischemic hypothermia in humans must be maintained for a minimum of 6–12 h to be effective (24). Hence a potential role of ICSI in the acute management of ischemic stroke is for rapid induction of hypothermia, whereas mild systemic hypothermia via surface or endovascular whole body cooling can maintain hypothermia.

Confirmation of body cooling in jugular venous model. Through Eq. 9, the jugular venous model makes an assumption that core temperature will be affected only by cool blood returning from the brain. In reality, body temperature could increase through shivering or decrease through heat loss to the environment. Our assumption is based on the observation that, in normal temperature homeostasis, bodily heat sources and losses balance one another out to maintain a constant temperature and therefore, for temperature changes resulting from the addition of a heat sink such as a cold infusion, heat loss to the environment will also be matched by any metabolic sources of heat.

This assumption is confirmed with data from eight direct intravascular (IV) cold fluid infusion studies (11 groups of patients, Table 4). The temperature drop from such an infusion is employed with the following equation (see APPENDIX):

$$\frac{dT_{\text{core}}}{dt} = \frac{\rho_{\text{blood}}c_{\text{blood}}(T_{\text{infusion}} - T_{\text{core}})F_{\text{infusion}}}{m_{\text{body}}c_{\text{body}}}$$  \hspace{1cm} (18)$$

This equation is completely analogous to Eq. 9 and also does not include terms for metabolic sources or heat losses to the environment.

Figure 6 shows the body core temperature drop in the model from venous return compared with the body core temperature drop that would incur, according to Eq. 18, from an equivalent IV infusion of the same temperature and flow rate (30 ml/min). As expected, the resultant temperature from the IV infusion is slightly lower than in the venous return model because in the venous return model the brain temperature remains lower than in the rest of the body. However, the temperature difference between the venous return and IV infusion curves remains less than 0.1°C because the brain model mass (1.8 kg) is only 2.5%
of the body’s mass. This demonstrates that infusing the body through the carotids yields a similar bodily temperature change as an IV infusion. However, brain temperature decreases are much greater via the intracarotid route.

Table 4 summarizes the IV infusion studies and includes the reported temperature drops from the studies along with the predicted temperature drops according to Eq. 18. The average temperature difference between the actual and predicted drop (actual minus predicted) was 0.24°C (standard deviation is 0.57°C). For patient groups that were not treated with sedative and/or antishivering medications (6 groups), the average temperature difference between the actual and predicted drop was 0.0°C (standard deviation is 0.67°C), whereas groups that were treated with sedative and/or antishivering medications (5 groups), the average temperature difference between the actual and predicted drop was 0.53°C (standard deviation is 0.24°C). These data demonstrate that the reported core temperature responses to an infusion of cold saline are well within the predicted values of the present study, especially for the case in which no antishivering or sedative drugs are administered.

Limitations of the model. The present model has several limitations: 1) The intracranial anatomy was simplified. The geometry of the head was modeled as a hemisphere, but the real shape of the head is not exactly hemispherical. However, a careful selection of appropriate dimension yielded a brain volume of 1,285 ml, a value halfway between the average male and female brain (30). Moreover, the model omitted the dura matter and the cerebrospinal fluid (CSF). This layer was omitted because it is too thin (≈2 mm), and the thermal properties of the CSF are very similar to those of the brain tissue (8, 38). 2) The present model assumes constant and equal rates of heat transfer loss and heat generation inside the body. In reality, hypothermia-induced shivering will disturb this equilibrium and heat generation will exceed loss, resulting in a possible overestimation of body core cooling from the cooled jugular venous return. However, effective neuromuscular blockade in a clinical setting will counteract much of the effect of shivering. However, data from IV infusion studies (see above discussion) suggest that for modest temperature drops of 1–2°C, use of antishivering drugs is associated with temperature decreases greater than what would be theoretically predicted. However, in ICSI, brain temperatures would be considerably lower than core temperature, which might make shivering a greater factor. 3) The Pennes equation describes a
continuum model where heat and mass transport are averaged over a representative unit volume. Continuum models are not able to predict the variation in temperature in the immediate vicinity of large, discrete blood vessels. However, the results obtained from a discrete vessel thermal model agreed well with Pennes’s continuum model (49). 4) The model assumes that temperature and hematocrit control the CBF independently. In theory, it is plausible, although not likely, that a reduced hematocrit may modify the cerebrovascular response to hypothermia, and vice versa. 5) In the model it is assumed that the dependence of CBF on local temperature and hematocrit is the same as that for global temperature and hematocrit. Several animal experiments (25, 33, 50) have confirmed that there are not significant differences in the reduction of CBF between systemic cooling and selective brain cooling. Although, to the best of our knowledge, there are no similar studies investigating potential differences between local and systemic hemodilution, it is reasonable to assume that perfusion increases due to hemodilution are also locally mediated. Furthermore, a fetal study has reported that vascular responses to oxygenation changes in the brain are locally mediated and occur within 3 s (34), suggesting that CBF dependence on local hematocrit should be the same as its dependence on global hematocrit.

APPENDIX

If a volume of fluid with volume $V_{\text{fluid}}$, density $\rho_{\text{fluid}}$, heat capacity $c_{\text{fluid}}$, and temperature $T_{\text{fluid}}$ mixes and equilibrates with the body that has mass $m_{\text{body}}$, heat capacity $c_{\text{body}}$, and temperature $T_{\text{body}}$, the new body temperature is

$$T_{\text{body,new}} = \frac{V_{\text{fluid}}\rho_{\text{fluid}}c_{\text{fluid}}T_{\text{fluid}} + m_{\text{body}}c_{\text{body}}T_{\text{core,old}}}{V_{\text{fluid}}\rho_{\text{fluid}}c_{\text{fluid}} + m_{\text{body}}c_{\text{body}}} \quad (A1)$$

If this volume is infused at rate $F_{\text{fluid}}$, then the body temperature is updated in this equation according to

$$T_{\text{body}}(t + \Delta t) = T_{\text{body}}(t) + \frac{F_{\text{fluid}}(\rho_{\text{fluid}}c_{\text{fluid}}T_{\text{fluid}} + m_{\text{body}}c_{\text{body}}T_{\text{body}}(t))}{F_{\text{fluid}}(\rho_{\text{fluid}}c_{\text{fluid}} + m_{\text{body}}c_{\text{body}})} \quad (A2)$$

Equation A2 can be rearranged to

$$T_{\text{body}}(t + \Delta t) - T_{\text{body}}(t) = \frac{\rho_{\text{fluid}}c_{\text{fluid}}T_{\text{fluid}} - m_{\text{body}}c_{\text{body}}}{m_{\text{body}}c_{\text{body}}} F_{\text{fluid}}(t + \Delta t) \quad (A3)$$

In the limit where $\Delta t \rightarrow 0$, A3 is rewritten as

$$\frac{dT_{\text{core}}}{dt} = \frac{\rho_{\text{fluid}}c_{\text{fluid}}(T_{\text{fluid}} - T_{\text{body}})F_{\text{fluid}}}{m_{\text{body}}c_{\text{body}}} \quad (A4)$$

For Eq. 18, the fluid is the cold infused saline. For Eq. 9, the fluid is cold venous blood which returns from the brain. The rate of this flow is determined simply by integrating total blood perfusion throughout the brain model:

$$F_{\text{venous}} = \int \int \int \alpha(r) d\bar{r} \quad (A5)$$

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THEORETICAL HUMAN MODEL OF SELECTIVE BRAIN COOLING


