11C-Iodoantipyrine for the Measurement of Regional Cerebral Blood Flow by Positron Emission Tomography

Validation Studies

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SUMMARY Positron emission tomography (PET) makes it possible to employ an in vivo autoradiographic paradigm to measure regional cerebral blood flow (rCBF) in man. In this study, we synthesized the positron-emitting radiopharmaceutical 11C-iodoantipyrine (11C-IAP) and validated its suitability as a CBF tracer. 11C (T1/2 = 20.4 min) was produced by the (p,a) nuclear reaction on 14N. 11C-methyl iodide was used to methylate 3-methyl-1-phenyl-2-pyrazolin-5-one to form 11C-antipyrine, which was iodinated. Radiochemical purity of the 11C-IAP product was 93-98% except as described below. rCBF was measured with 11C-IAP in nitrous oxide-anesthetized Wistar rats by the method of Indicator fractionation, and values were compared with rCBF values measured with simultaneously administered commercially produced 11C-IAP. rCBF was studied over a range of arterial Pco2 values (31-58 mm Hg, mean 43.0 ± 3.5). Mean rCBF data for the 2 tracers agreed to within 4.8% for cerebral hemispheres, 3.8% for cerebellum, and 5.3% for brainstem. Mean values (± SEM) for rCBF using 11C-IAP were 1.67 ± 0.20 ml gm-1 min-1 for cerebral hemispheres; 1.31 ± 0.17 for cerebellum; and 1.50 ± 0.21 for brainstem. When chromatographic analysis revealed tracer impurity, rCBF, as measured with 11C-IAP, fell consistently below values obtained with 11C-IAP. The data indicate that 11C-IAP, when properly synthesized and submitted to batch-by-batch quality control, may be suitable for measuring rCBF in man by emission tomography.

Materials and Methods

Synthesis of 11C-Iodoantipyrine

Carbon-11 (T1/2 = 20.4 min) was prepared in a CS-30 cyclotron (Cyclotron Corp.) by the 14N(p,a)11C nuclear reaction. "No-carrier-added" 14CO2 was synthesized by the method of Finn and Wolf, and 11C-methyl iodide was prepared from it by reduction with lithium aluminum hydride and distillation of the labelled methanol through hydriodic acid. This, in turn, was reacted with 3-methyl-1-phenyl-2-pyrazolin-
S-one to produce $^{14}$C-antipyrine plus other, undesired, methylated products which were removed on a silica gel column. $^{14}$C-iodoantipyrine was then prepared by iodination of $^{14}$C-antipyrine and was separated from the latter and from inorganic iodine residues on a silica gel column. The product was sterilized by Millipore filtration. Analyses by means of thin-layer chromatography and high performance liquid chromatography confirmed the product to be $^{14}$C-iodoantipyrine with a radiochemical purity of 93–98%, except in the special instances to be described below. Specific activity was approximately 30 Ci/m mole. Campbell and co-workers have presented a complete account of this synthesis.18

Animal Preparation

Wistar rats weighing 300–400 gm were anesthetized with diethyl ether, tracheostomized, immobilized with d-tubocurarine (1.8 mg i.p.), and ventilated mechanically on mixtures of 70% nitrous oxide and 30% oxygen. Catheters were inserted into one external jugular vein and one or both femoral arteries. Mean arterial blood pressure was measured by a transducer (Statham) and displayed on an analog meter (Stentor). Arterial blood gases were monitored periodically with a multi-electrode analyzer system (Corning). Rectal temperature was maintained at 37°C by a thermostatically controlled heating lamp.

Regional Cerebral Blood Flow (rCBF)

rCBF was measured by the method of indicator fractionation.19 In these studies, we wished to compare rCBF as measured by $^{14}$C-IAP synthesized in our laboratory with rCBF measured using commercially prepared $^{14}$C-IAP (4-N-[methyl-$^{14}$C] — iodoantipyrine, New England Nuclear, specific activity 40–60 mCi/m mole). Thus, a mixture of 100–500 μCi of $^{14}$C-IAP and 30 μCi of $^{14}$C-IAP dissolved in 300 μl normal saline was injected as a bolus into the external jugular vein via a short catheter. An infusion/withdrawal pump (Harvard Apparatus Co.) was used to withdraw an arterial “reference organ” blood sample at a precalibrated, constant rate (approximately 0.15 ml/min) into a 50 cm-long P.E. 50 polyethylene catheter via a 250 μl microliter syringe (Hamilton). The withdrawal of arterial blood was begun just prior to tracer injection. Seven sec after injection, the animal was decapitated, and the “reference organ” arterial catheter was simultaneously extracted from the animal and its contents delivered into a vial containing 500 μl isopropanol-Soluene-350 (Packard) (1:1, v/v), to which 200 μl hydrogen peroxide was added. The brain was removed and dissected into the two cerebral hemispheres, cerebellum, and brainstem. Each cerebral hemisphere was bisected into anterior and posterior quadrants. All brain samples were weighed. A sodium iodide well counter was used to measure $^{14}$C activity of the “reference organ” blood sample and brain samples; this instrument detected the 511 keV emission of $^{14}$C but was insensitive to the β-emission of $^{14}$C. The $^{14}$C count rates were corrected for background activity and for $^{14}$C decay.

Measurement of $^{14}$C activity was delayed by at least one day to permit complete decay of $^{14}$C. $^{14}$C activity was assessed by measurement of its β-emission in a liquid scintillation spectrometer. Brain samples were solubilized in Soluene-350 and counted in Dimilume-30 (Packard). The blood sample was counted in Instagel (Packard) acidified with HCl. The external standard ratio method of correction for quenching was employed.

For each tracer, rCBF was calculated from the equation:

$$rCBF \ (ml \ gm^{-1} \ min^{-1}) = \frac{Brain \ activity \ per \ gm \times \ "Ref. \ organ" \ flow \ (ml \ min^{-1})}{"Ref. \ organ" \ activity}$$

Results

Physiological Data

Mean arterial blood pressure in the 9 animals of this series was 141 ± 5 mm Hg (mean ± SEM). Arterial Pco2 was intentionally varied from 31 to 58 mm Hg in individual animals in order to produce a range of rCBF values. Mean arterial blood values (± SEM) were: Pao2, 115 ± 8 mm Hg; Pco2, 43.0 ± 3.5 mm Hg; pH, 7.357 ± 0.032.

Regional Cerebral Blood Flow

Figure 1A compares rCBF as measured by UC-IAP and $^{14}$C-IAP in 34 cerebral hemispheral samples from 9 rats. There was excellent agreement between the 2 tracers. Statistical analysis of the data was facilitated by computing a weighted mean cerebral hemispheral blood flow for each animal; these data are shown in figure 1B. Again, there was close agreement between tracers. The paired Student's t-value for the data was 2.71 (p < 0.05). rCBF values were well segregated according to ranges of arterial Pco2 (fig. 1B).

Figure 2 displays rCBF values in cerebellum and brainstem; again, values determined by $^{14}$C- and $^{14}$C-IAP agreed closely. Table 1 summarizes the rCBF data. Mean rCBF data for the 2 tracers agreed to within 4.8% for cerebral hemispheres, 3.8% for cerebellum, and 5.3% for brainstem. As table 1 demonstrates, mean rCBF values obtained with $^{14}$C-IAP were lower than $^{14}$C-IAP values for all 3 structures. A Student's t-test revealed no significant differences between the respective $^{14}$C and $^{14}$C mean values. Nevertheless, the rather large variance associated with each

### Table 1: Regional Cerebral Blood Flow (rCBF) (ml gm⁻¹ min⁻¹)

<table>
<thead>
<tr>
<th></th>
<th>$^{14}$C-Iodoantipyrine</th>
<th>$^{14}$C-Iodoantipyrine</th>
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<tbody>
<tr>
<td>Cerebral hemispheres</td>
<td>1.67 ± 0.20</td>
<td>1.59 ± 0.17</td>
</tr>
<tr>
<td>Cerebellum</td>
<td>1.32 ± 0.17</td>
<td>1.27 ± 0.16</td>
</tr>
<tr>
<td>Brainstem</td>
<td>1.50 ± 0.21</td>
<td>1.42 ± 0.18</td>
</tr>
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*Mean ± SEM, n = 8-9.*

Pco2 = 43.0 ± 3.5 mm Hg; range 31.1–51.8 mm Hg.
Figure 1A. rCBF in 34 cerebral hemispheric samples from 9 rats as measured with \(^{14}\text{C}\) and \(^{11}\text{C}\)-IAP. The dotted line is the line of identity; the solid line is the least-squares fit to the data.

Figure 1B. Weighed mean cerebral hemispheric CBF as measured in 9 rats with \(^{14}\text{C}\) and \(^{11}\text{C}\)-IAP. Filled circles represent rats with arterial Pco\(_2\) 31-34 mm Hg; open circles, 37-40 mm Hg; and triangles, 50-58 mm Hg.

Figure 2. rCBF in cerebellum (fig. 2A) and brainstem (fig. 2B) as measured in 8 rats with \(^{14}\text{C}\) and \(^{11}\text{C}\)-IAP. The CBF in cerebral hemispheres was highly correlated with arterial Pco\(_2\) (r = 0.994, p < 0.01). The corresponding value as measured by \(^{14}\text{C}\)-IAP in the 9 animals of this series is 0.048 ml gm\(^{-1}\) min\(^{-1}\) per mm Hg change of arterial Pco\(_2\). The corresponding value as measured by \(^{11}\text{C}\)-IAP does not attain statistical significance.
Table 2  Mean (\(^{113}\)C-CBF/\(^{14}\)C-CBF) Ratio for Brain Samples From Individual Rats*  

<table>
<thead>
<tr>
<th>Animal #</th>
<th>Mean</th>
<th>SEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.03</td>
<td>0.008</td>
</tr>
<tr>
<td>2</td>
<td>0.98</td>
<td>0.007</td>
</tr>
<tr>
<td>3</td>
<td>0.99</td>
<td>0.004</td>
</tr>
<tr>
<td>4</td>
<td>0.99</td>
<td>0.013</td>
</tr>
<tr>
<td>5</td>
<td>0.92</td>
<td>0.016</td>
</tr>
<tr>
<td>6</td>
<td>0.97</td>
<td>0.002</td>
</tr>
<tr>
<td>7</td>
<td>0.95</td>
<td>0.003</td>
</tr>
<tr>
<td>8</td>
<td>0.89</td>
<td>0.007</td>
</tr>
<tr>
<td>9</td>
<td>0.95</td>
<td>0.003</td>
</tr>
</tbody>
</table>

Series mean: 0.96  
SD: 0.04  
95% confidence limits: 0.88-1.04  

*\(n = 4-6\) samples per animal.

with \(^{13}\)C-IAP was 0.041. These values exceed those reported by other workers in the nitrous oxide-anesthetized rat\(^8\) and in other species.\(^1^\) This discrepancy may be due in part to the limited number of data points in our series, particularly in the mid-range of PCO\(_2\) (fig. 3).

Figure 4 emphasizes the importance of performing quality control on each batch of \(^{13}\)C-IAP prior to its use in measuring rCBF. In a study in which thin-layer chromatography of the \(^{13}\)C-product revealed no IAP to be present, the apparent "rCBF" as measured with this product was markedly reduced compared with values obtained with \(^{14}\)C-IAP (fig. 4A). In another study, the \(^{13}\)C-product had been heated to enhance its solubilization; this resulted in heat-decomposition of the product. rCBF values obtained with the \(^{13}\)C-product were consistently below those obtained with \(^{14}\)C-IAP (fig. 4B). The mean value for the (\(^{113}\)C-CBF/ \(^{14}\)C-CBF) ratio was 0.772 ± 0.001 (SEM). These data suggest that the heat-decomposition may have yielded

\(^{13}\)C-antipyrine, which, by virtue of its greater diffusion-limitation, tends to underestimate rCBF of gray-matter structures relative to iodoantipyrine.\(^9\)

Discussion

The data of this study demonstrate that \(^{13}\)C-iodoantipyrine, when synthesized as described and
subjected to proper quality control, can be used for accurately measuring rCBF in the experimental animal and thus would be expected to be suitable for the emission-tomographic measurement of rCBF in man. Certain qualifications, however, must be appended. As the data of figure 4 suggest, batch-by-batch quality control of the 11C-product is essential if valid rCBF results are to be assured. Antipyrine, the immediate precursor of 11C-IAP, has been shown by several workers to be significantly permeability-limited at normal rates of gray-matter blood flow and to produce a falsely low estimate of rCBF. The percentage by which antipyrine underestimates rCBF relative to IAP is calculated from the data provided by Sakurada et al. to average 39% for gray-matter structures of the conscious rat. In the study shown in figure 4B, the 23% decrement observed approximates this value and suggests that the 11C-product in that instance may have consisted in part of antipyrine or a related, permeability-limited 11C-labelled substance.

Apart from the necessity for proper quality control, an additional disadvantage of 11C-IAP is the relative difficulty of scaling its synthesis up to the 5-10 mCi amount required for human emission-tomographic imaging. In this respect, 11O-labelled water (T1/2 123 sec), which we are also investigating, appears to be a superior tracer for human rCBF studies inasmuch as it can be synthesized readily with high purity and ample yield (typically, 50 mCi in a volume of 50 μl) by a simple and straightforward strategy.

For tomographic studies of rCBF in man employing an autoradiographic paradigm, an estimated dose of 5-10 mCi of 11C-IAP would be required, to be administered by intravenous infusion over 1-2 min. The resulting radiation exposure to the patient is determined by the physical half-life of the radionuclide and the biodistribution of the radiopharmaceutical. IAP has been shown to approach equilibrium in the blood within 10 min of its intravenous administration and to have a calculated distribution volume approximating 65% of body weight. Significant amounts of iodide detach from the IAP molecule within 15 min, and up to 70% of this iodide appears in the urine within 24 h. The resulting 11C-antipyrine has a biologic half-life of 7 to 20 h in plasma and is distributed throughout body water. Thirty to 40% of the antipyrine is oxidized to 4-hydroxyantipyrine, rapidly conjugated to the glucuronide and possibly sulfate, and excreted. The metabolic fate of the remainder is not known. The physical half-life of 11C (20.4 min) is considerably shorter than the biological half-life of either IAP or its metabolite, antipyrine, and is thus the chief determinant of the radiation dose to the patient. If one assumes a uniform whole body distribution and 100% retention of the tracer, an injected dose of 10 mCi in a 70 kg man would result in an absorbed dose of 112 mRad to the whole body. This is an acceptable level to permit its use for rCBF studies in man.

We have recently developed and validated an "in vivo autoradiographic" strategy for measuring regional cerebral blood flow by positron emission tomography. In this method, blood flow is computed from the time-integrated cerebral activity curve resulting from a modified ramp intravenous infusion of a positron-emitting blood flow tracer such as 11O-water or 11C-iodoantipyrine administered over an interval of one min or more. This method holds promise for the measurement of rCBF in man by positron emission tomography.

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References
A VARIETY of non-invasive techniques have been developed for the detection of extracranial arterial disease (EAD): Some of these methods, such as the supraorbital Doppler, \(^1\) \(^2\) ophthalmodynamometry \(^3\) and ocular pneumoplethysmography \(^4\) are inexpensive and easily performed. Their validity is, however, limited to the detection of high-grade stenosis or occlusion of the carotid arteries. \(^5\) \(^6\) An accurate differentiation between stenosis and occlusion of the carotid arteries is impossible and the exact site of obstruction cannot be localized.

The more sophisticated application of the Continuous Wave (CW)-Doppler technique for direct insonation of the carotid arteries in the neck has considerably improved the value and reliability of the non-invasive examination, particularly for the carotid artery system. \(^7\) \(^8\) \(^9\) \(^10\) \(^11\) \(^12\) By continuous scanning of the course of the extra-cranial arteries from the supraclavicular to the submandibular region it is possible to detect with accuracy the size, extent and location of lesions producing an obstruction of the lumen of about 50% or more. The method can be further refined by spectrum analysis of the Doppler signals \(^13\) allowing the additional detection of lesions producing obstructions of even less than 50% due to atherosclerotic changes in the normal laminar flow within the vessels. \(^14\) With the new combination of real-time B-scan imaging and Doppler systems \(^15\) \(^16\) \(^17\) it may become possible to achieve a degree of resolution sufficient for the detection of even small ulcerated lesions of the arterial wall.

It has been reported that use of the Doppler technique to detect flow abnormalities in the vertebral arteries (flow reduction or steal phenomena) provides information on the adequacy of the posterior brain circulation. \(^10\) \(^11\) \(^12\) Although CW-Doppler does not as yet yield quantitative information about cerebral perfusion, the evidence it provides of significant variations in blood flow velocity between the carotid and vertebral artery systems — as well as knowledge of the collaterals — may be of substantial help in making an

SUMMARY Investigations of the incidence and the extent of the asymptomatic early stages of extracranial arterial disease (EAD) have been restricted for methodical reasons. Direct Continuous Wave-Doppler examination has given highly accurate results in the location and correct estimation of the degree of EAD both for the carotid (97%) and the vertebral arteries (90%), as shown from a detailed comparison with carotid (n = 604) and vertebral (n = 426) angiograms. Compared with this degree of reliability, the validity of normal auscultation for the diagnosis of EAD is shown to be poor. If bruits are taken as the only signs of associated EAD in patients with systemic atherosclerosis, only 27.6% in a group of 123 patients would have been correctly diagnosed. This parallels the number of false-positives (22.6%) in patients with normal results. The frequency and degree of EAD was studied by the use of direct Doppler examination in 2009 neurologically asymptomatic patients admitted either with severe vascular (n = 375) or coronary atherosclerosis (n = 264) or with high-risk factors (n = 1370). The frequency was significantly higher (32.8%) in patients with peripheral vascular disease than in those with coronary artery disease (6.8%) and in risk-factor patients (5.9%). The combination and degree of vessel involvement are presented in detail and their possible prognostic significance discussed.

Incidence of Asymptomatic Extracranial Arterial Disease

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