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Abbreviations:
CBF = cerebral blood flow
ICA = internal carotid artery
VFR = volume flow rate
2D = two-dimensional

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Effect of Age on Cerebral Blood Flow: Measurement with Ungated Two-dimensional Phase-Contrast MR Angiography in 250 Adults[1]

PURPOSE: To determine the normal values and effects of age and sex on total cerebral blood flow (CBF) as measured with ungated two-dimensional phase-contrast magnetic resonance (MR) angiography.

MATERIALS AND METHODS: Volume flow rates in the basilar artery and both internal carotid arteries were measured on two-dimensional phase-contrast MR angiograms obtained in 250 subjects (age range, 19–88 years; mean age, 50 years) undergoing MR imaging because of indications other than cerebrovascular disease. Volume flow rates for the three arteries were summed to obtain the total CBF, and the values were analyzed in terms of age and sex.

RESULTS: Mean total CBF was 616 mL/min ± 143. There was a significant yearly decrease with age in total CBF of 4.8 mL/min ($P < .001$). Mean total CBF ranged from 748 mL/min ± 121 to 474 mL/min ± 105 in subjects aged 19–29 and 80–89 years, respectively. No sex differences were found. Mean relative contributions of the right and left internal carotid arteries and the basilar artery to total CBF were 41%, 40%, and 19%, respectively, with no substantial change due to age.

CONCLUSION: Ungated two-dimensional phase-contrast MR angiography is a useful, noninvasive technique for assessing total CBF. By using this technique, a significant decrease in total CBF with age was demonstrated.

With two-dimensional (2D) phase-contrast magnetic resonance (MR) angiography, blood flow can be measured in any individual blood vessel in a simple, noninvasive manner and without the need for an intravascular agent. This MR technique is based on the principle that magnetic field gradients introduce a phase shift in flowing spins that is proportional to blood flow velocity. On the basis of this phase shift, blood flow velocity (expressed in centimeters per second) and volume flow rate (VFR, expressed in milliliters per minute) can be calculated for each vessel (1).

In most studies that involve phase-contrast MR angiography, the blood flow measurements are acquired with use of cardiac triggering. Triggered, or gated, phase-contrast MR angiography has been applied to the vessels in the lower extremities (2), the aorta and/or pulmonary veins (3–6), the aorta and its major branches (7,8), and the vessels to the brain (6,9–16). It has been shown (17–20) that for the assessment of blood vessels supplying the brain, the measurements can be performed without cardiac triggering, which thus makes the method even more simple and rapid to perform.

Quantitative measurement of blood flow to the brain may be helpful for distinguishing patients at risk for cerebral ischemia or infarction caused by a decrease in this flow. Measurement of the VFR in the internal carotid artery in patients with possible carotid artery disease may be helpful in identifying vascular stenosis (13,14,16). Before one can interpret cerebral and internal carotid artery flow values in patients, however, the normal values and their changes with age and sex must be assessed. Until recently, blood flow to

the brain as a whole (cerebral blood flow [CBF]) or to specific brain areas (regional or local CBF) could be measured only with methods that were technically difficult, time-consuming, and relatively expensive and that may subject the patients to ionizing radiation (21–45). In most studies, CBF was determined in patients with vascular disease or other abnormalities. However, there are only limited data about normal CBF values, because relatively small numbers of healthy individuals have undergone these tests. The available data were inconsistent with regard to whether CBF values were dependent on age. Some authors (22,29,31–33,35,36,40) have suggested that CBF decreases with increasing age, whereas others (9,25,26, 28,38,43,45) did not find evidence of such a decline.

The purpose of this study was to determine the normal total CBF by measuring the VFR of the basilar artery and both internal carotid arteries with the use of ungated 2D phase-contrast MR angiography. In addition, we assessed the effect of age and sex and the relative contribution of each vessel to the total CBF.

MATERIALS AND METHODS

Institutional review board approval was obtained for this study, and informed consent was obtained from all individuals involved in the study.

The study population consisted of 250 adults from three study groups. The first group consisted of 20 healthy university students (10 men, 10 women; age range, 19–24 years; mean age, 21 years) who participated in a study that involved MR imaging of the intracranial vasculature. There was no evidence of physical abnormalities in the medical histories of these students.

The second group consisted of 142 consecutive adults (74 men, 68 women; age range, 19–70 years; mean age, 42 years) who underwent MR imaging and MR angiography of the brain to screen for the presence of aneurysms as part of an ongoing epidemiologic study for familial intracranial aneurysms in first-degree relatives of patients admitted because of subarachnoid hemorrhage. At review of the medical histories of this group, the following relevant risk factors for or symptoms of atherosclerotic vascular disease were found: hypertension (n = 18), diabetes mellitus (n = 2), transient ischemic attack or cerebrovascular accident (n = 2), and angina pectoris or myocardial infarction (n = 4).

The third group consisted of 88 consecutive subjects (38 men, 50 women; age range, 60–88 years; mean age, 70 years) who underwent MR imaging of the head as participants in a large epidemiologic study of the cerebrovascular risk factors in elderly individuals. Relevant risk factors or disease in this group were hypertension (n = 29), diabetes mellitus (n = 8), transient ischemic attack or cerebrovascular accident (n = 5), and angina pectoris or myocardial infarction (n = 2). The mean age of the entire study group of 250 subjects was 50 years.

All studies were performed with a 1.5-T MR unit (Gyroscan NT; Philips Medical Systems, Best, the Netherlands) equipped with standard hardware and software. In all cases, measurements of flow with 2D phase-contrast MR angiography were performed by choosing a transverse imaging plane at the level of the skull base perpendicular to the precavernous section of both internal carotid arteries (ICAs) and the middle or distal part of the basilar artery. The position of this transverse section was determined by using a sagittal 2D phase-contrast MR angiographic scout image (Fig 1a). Imaging parameters were 16.4/9.3 (repetition time msec/echo time msec), 7.5° flip angle, 188 × 250-mm rectangular field-of-view, 5-mm section thickness, 154 × 256 matrix, eight signals acquired, and 100-cm/sec velocity encoding. Velocity encoding was accomplished by subtracting two images obtained with opposed, bipolar, velocity-encoding gradients. The total imaging time was 40 seconds, and no cardiac triggering was used.

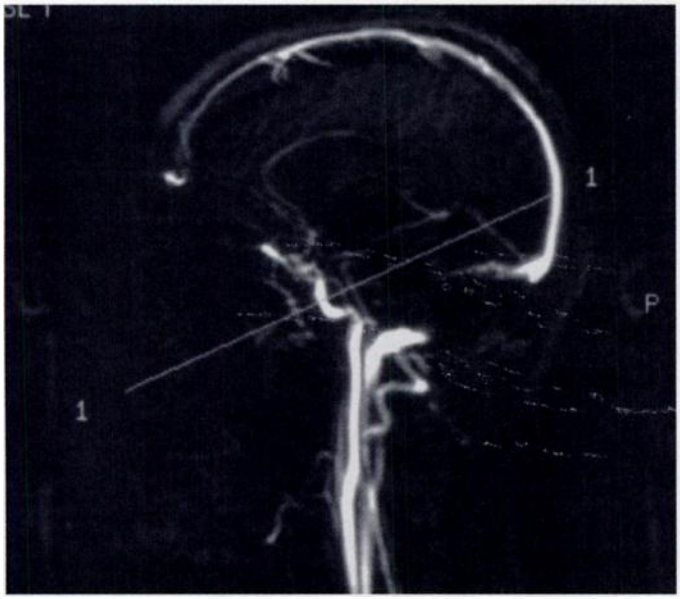
Flow velocity data were calculated from the phase-difference images by drawing circular regions of interest for the basilar artery and each ICA; these regions of interest encompassed the entire vessel lumen (Fig 1b). The resultant value of the mean signal intensity in each region of interest represented the spatial- and time-averaged flow velocity in that vessel, which was expressed in centimeters per second or per minute. By multiplying this averaged velocity by the cross-sectional area of the pixels in the region of interest, the VFR could be calculated; the VFR represented the average blood flow in the vessel and was expressed in milliliters per minute (Fig 1c) (17–19,46). To determine the total CBF, the VFR values from both ICAs and from the basilar artery were summed. The diameter (mean ± SD) of each vessel was calculated by using the area measurements of the regions of interest. To determine the random error in measuring total CBF on ungated 2D phase-contrast MR angiograms, repeated flow measurements (20 measurements) were performed in a healthy volunteer by using the same phase-contrast imaging protocol.

For data analysis, age was categorized in terms of decades. Mean VFR values and SDs for each vessel and for total CBF were calculated for the entire group and for each age decade. Also, the relative contributions to the total CBF of each ICA and of the basilar artery were calculated in each subject, and mean values plus or minus the SD for this contribution within each age group were determined. Differences between VFR values for the left and the right ICA were tested with a paired Student t test, and differences between the sexes were determined with an unpaired Student t test. The effect of age on total CBF was evaluated by using linear regression analyses for the entire group and for a subgroup of those individuals with no risk factors for or symptoms of atherosclerotic disease. The combined effect of age and sex on total CBF was determined by using a multiple linear regression analysis.

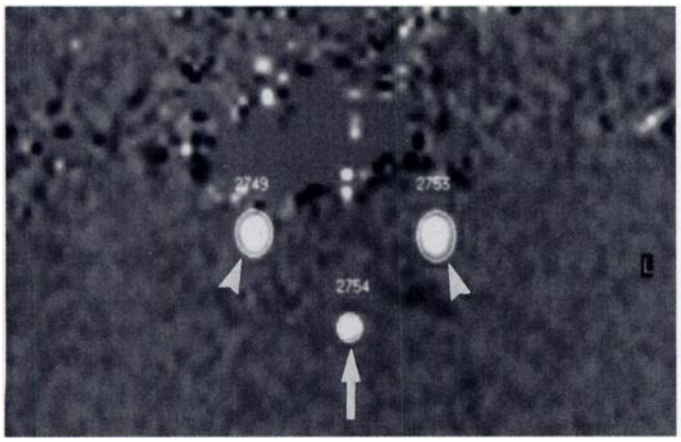
RESULTS

The mean total CBF for the entire group was 616 mL/min ± 143 and ranged from 748 mL/min ± 121 for the youngest group (aged 19–29 years) to 474 mL/min ± 105 for the oldest (aged 80–89 years) (Table 1, Fig 2). There was a gradual and continuous decrease in total CBF with age; this decrease was significant, as demonstrated at a linear regression analysis. For all 250 subjects, the reduction in total CBF was 4.8 mL/min/y (slope = −4.8, intercept = 859, $P < .001$). For the subgroup of 190 individuals with no risk factors for or symptoms of atherosclerotic disease, this reduction was 4.6 mL/min/y (slope = −4.6, intercept = 851, $P < .001$). Sex had no influence on total CBF ($P = .4$, multiple linear regression analysis).

In the entire study population of 250 subjects, the mean VFR was 250 mL/min ± 69 for the right ICA, 247 mL/min ± 72 for the left ICA, and 120 mL/min ± 47 for the basilar artery (Table 1). In the entire study population and within each age group, there were no significant differences in the VFR for the left and right ICAs ($P = .5$ and $P > .15$, respectively). The relative contribution of the three individual vessels to the total CBF was 41% ± 6 for the right ICA, 40% ± 7 for the left ICA, and 19% ± 6 for the basilar artery. These relative contributions remained almost constant for all age decades: The range was 39%–43% for the right ICA, 38%–42% for the left ICA,



a.



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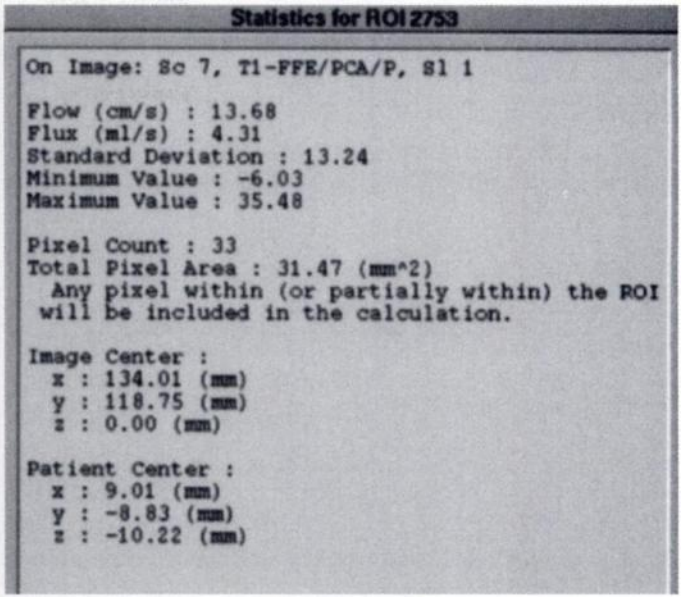

c.

Figure 1. **(a)** Sagittal 2D phase-contrast MR angiographic scout image (13.7/7, 20° flip angle) shows the position of the section (line, *1*) obtained at ungated 2D phase-contrast MR angiography. The section position is at the level of the skull base, perpendicular to the precavernous section of the ICAs and the middle portion of the basilar artery. *P* = posterior. **(b)** Axial-oblique 2D phase-contrast MR angiographic phase image (16.4/9.3, 7.5° flip angle) with regions of interest drawn around the basilar artery (arrow, *2754*) and both ICAs (arrowheads). *2749* = region of interest for right ICA, *2753* = region of interest for left ICA. **(c)** Workstation screen shot shows the results of the statistical analysis of the region of interest in the left ICA, with the values of spatial- and time-averaged VFR (*Flux*) for this blood vessel. Total CBF is calculated by summing the VFR values from the basilar artery and the left and right ICAs.

and 17%–21% for the basilar artery (Table 1). Therefore, the reduction in total CBF with age was equally distributed across all three vessels. The right and left ICAs each had a mean diameter of 5.9 mm ± 0.8, and that of the basilar artery was 4.2 mm ± 0.7. Determination of the precision of VFR measurements in a healthy volunteer revealed a random error of 30 mL/min (approximately 5%) for total CBF.

DISCUSSION

The 2D phase-contrast MR angiographic technique combined with cardiac triggering (cine 2D phase-contrast MR angiography) has been validated for flow measurement in several in vitro and in vivo studies. In flow phantoms, cine 2D phase-contrast MR angiography yielded a close correlation between the actual and the measured flow for wide ranges of flow velocities in steady flow patterns (4,5), as well as for velocities in pulsatile flow patterns (6,19). In in vivo experiments, cine 2D phase-contrast MR angiography also allowed good reproducibility of flow measurements. For instance, blood flow measured simultaneously with cine 2D phase-contrast MR angiography and implanted ultrasound flow meters in various blood vessels in dogs did not vary significantly across a large range of arterial and venous blood flow rates (47). Results of cine 2D phase-contrast MR angiography in humans have shown that the VFR in the main pulmonary artery correlates well with that in the right and left pulmonary arteries combined (4) and with that in the aorta (6). Other investigators (3,5) have reported a good correlation between the VFR measured with cine 2D phase-contrast MR angiography in the ascending aorta and/or main pulmonary artery and that measured with short-axis cine MR imaging of left ventricular stroke volume. These results indicate that cine 2D phase-contrast MR angiography can be regarded as a reliable technique for measuring flow in blood vessels. The use of cardiac triggering, however, makes the technique time-consuming because of the possible problems in obtaining good electrocardiographic registration, the relatively long acquisition times (3–10 minutes), and the complexity of data processing.

These problems can be prevented by using ungated 2D phase-contrast MR angiography, which does not require cardiac triggering. This makes ungated 2D phase-contrast MR angiography fast and easy to perform. In vitro studies have shown that ungated 2D phase-contrast MR angiography provided a high correlation between the measured VFR and actual flow rates in both constant (6,48,49) and pulsatile flow patterns (17,49). In a

TABLE 1
MR Angiographic Measurements of VFR in the ICA and Basilar Artery and Total CBF according to Age in 250 Subjects

Age Range (y)‡	No. of Subjects§	VFR (mL/min)*			Total CBF (mL/min)†		
		Right ICA	Left ICA	Basilar Artery	Men	Women	All Subjects
All (50)	250 (122/128)	250 ± 69 (41 ± 6)	247 ± 72 (40 ± 7)	120 ± 47 (19 ± 6)	630 ± 146	604 ± 139	616 ± 143
19–29 (23)	43 (23/20)	294 ± 63 (39 ± 7)	303 ± 74 (40 ± 6)	152 ± 47 (20 ± 6)	757 ± 122	739 ± 122	748 ± 121
30–39 (34)	40 (21/19)	291 ± 70 (41 ± 7)	275 ± 79 (38 ± 8)	145 ± 43 (21 ± 5)	723 ± 140	699 ± 107	712 ± 125
40–49 (44)	41 (23/18)	258 ± 65 (41 ± 6)	250 ± 60 (40 ± 6)	115 ± 41 (18 ± 6)	612 ± 109	637 ± 127	623 ± 116
50–59 (54)	26 (13/13)	235 ± 58 (39 ± 6)	249 ± 48 (42 ± 7)	111 ± 40 (18 ± 5)	607 ± 95	583 ± 111	595 ± 102
60–69 (65)	59 (22/37)	221 ± 57 (41 ± 6)	209 ± 55 (39 ± 6)	107 ± 36 (20 ± 7)	551 ± 90	527 ± 105	536 ± 99
70–79 (74)	32 (15/17)	213 ± 60 (41 ± 7)	217 ± 64 (42 ± 8)	86 ± 46 (17 ± 8)	527 ± 131	508 ± 92	517 ± 110
80–89 (83)	9 (5/4)	201 ± 51 (43 ± 6)	188 ± 74 (39 ± 10)	86 ± 40 (19 ± 8)	443 ± 96	514 ± 116	474 ± 105

* Data are the mean ± SD. Numbers in parentheses are the relative percentage contribution ± SD to the total CBF.
† Data are the mean ± SD.
‡ Numbers in parentheses are means.
§ Numbers in parentheses are number of men/number of women.

phantom study, Bakker et al (19) tested ungated 2D phase-contrast MR angiography for three flow patterns. They found good agreement between measured and actual flow for monophasic, relatively weak pulsatile flow, such as that in the carotid arteries, but not for biphasic or triphasic flow, such as that in, for example, the lower extremities. For monophasic, relatively weak pulsatile flow patterns, the error between the measured and the true flow values was found to be less than 1%, which indicates the high accuracy of the technique. The reliability of this technique was further confirmed with in vivo study results (18,20) in which a good correlation was found between flow values in the carotid arteries measured with ungated 2D phase-contrast MR angiography and the values obtained with cine 2D phase-contrast MR angiography, with systematic errors of less than 3% between results obtained with the two techniques. Therefore, ungated 2D phase-contrast MR angiography appears to be a suitable technique for measuring flow in the blood vessels that supply the brain.

In this study, we measured the VFR of the three main vessels to the brain and found a statistically significant decrease in total CBF with age, with a mean yearly decrease of 4.8 mL/min. It was further shown that the mean values of the relative contribution of the right and left ICAs and the basilar artery to the total CBF remained almost constant throughout life (41%, 40%, and 19%, respectively). Similar to Marks et al (9), we estimated total CBF by summing the flow measurements of the three major vessels (the two ICAs and the basilar artery) to the brain. Because the point at which the blood flow of the basilar artery was measured was proximal to the origin of the superior cerebellar arteries, however, a small fraction of cerebellar flow was included in our total CBF calculations. In adults, the cerebellum accounts for approximately 10% of brain weight (50). Because the two other main vessels that supply the cerebellum, the anterior and posterior inferior cerebellar arteries, were not included in our measurements, and by assuming an equal contribution to cerebellar blood supply by the superior, anterior inferior, and posterior inferior cerebellar arteries, it is likely that our total CBF measurements were slightly overestimated by 3%–4%.

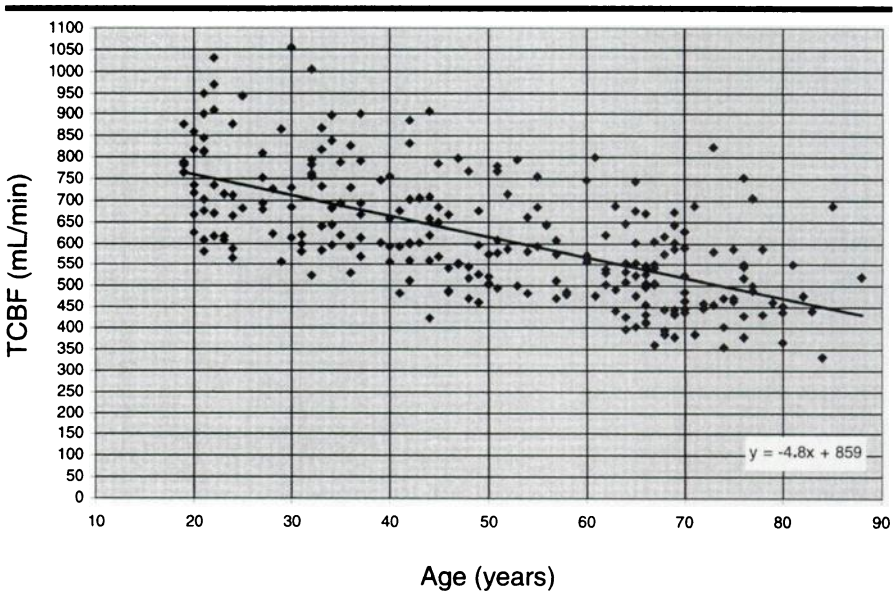

Figure 2. Graph shows total CBF (*TCBF*) according to age as measured on ungated 2D phase-contrast MR angiograms in 250 subjects.

TABLE 2
Normal Total CBF Values Reported in the Literature

Study	Year	Method	Subjects	Mean Age (y)	Blood Flow (mL/100 g/min)			Mean Total CBF (mL/min)	Decrease in CBF with Age?
					CBF	Gray Matter	White Matter		
Kety and Schmidt (21)	1948	N_2O	14 healthy young men	25	54	NR	NR	656	Yes
Fazekas et al (23)	1952	N_2O	9 with no cardiovascular or neurologic disease	34	54	NR	NR	656	Yes
Fazekas et al (23)	1952	N_2O	15 with no cardiovascular or neurologic disease	68	43	NR	NR	488	Yes
Fazekas et al (24)	1953	N_2O	18 subjects, mentally alert (n = 6) or with various degrees of deterioration (n = 12, no difference between these groups)	93	39	NR	NR	422	Yes
Shenkin et al (25)	1953	N_2O	12 normotensive individuals, no clinical evidence of arteriosclerosis	30	53	NR	NR	643	No
Sokoloff et al (27)	1953	N_2O	4 healthy nonhospitalized individuals	19	60	NR	NR	728	NR
Sokoloff et al (27)	1953	N_2O	7 healthy nonhospitalized individuals	23	52	NR	NR	631	NR
Meyer et al (30)	1978	Xe-133	15 healthy volunteers	36	54	78	19	638	Yes for gray matter, no for white matter
Melamed et al (31)	1980	Xe-133	44 healthy, nonhospitalized, normotensive individuals	42	54	NR	NR	638	Yes
Matsuda et al (32)	1984	Xe-133	105 healthy volunteers	42	56	NR	NR	662	Yes
Hojer-Pedersen (33)	1987	Xe-133	23 healthy control subjects	51	53	NR	NR	615	Yes
Fazekas et al (34)	1988	Xe-133	11 with no evidence of cerebrovascular diseases, no white matter lesions on MR images	58	43	64	17	506	NR
Hagstadius and Risberg (35)	1989	Xe-133	32 healthy male subjects	26	56	NR	NR	680	Yes
			32 healthy male subjects	40	50	NR	NR	591	NR
			33 healthy male subjects	59	44	NR	NR	518	NR
Shirahata et al (36)	1985	Xe-133	39 healthy adults	43	56	80	40	662	Yes
Sorteberg et al (37)	1989	Xe-133	8 healthy subjects	46	55*	NR	NR	639	NR
Leinsinger et al (38)	1994	Xe-133	41 healthy control subjects	45	63*	NR	NR	731	No
Meyer et al (39)	1981	Xenon CT	9 healthy control subjects	38	58†	82	29	685	NR
Tachibana et al (40)	1984	Xenon CT	20 healthy volunteers	56	51†	72	26	600	Yes for gray matter more than for white matter
Imai et al (41)	1988	Xenon CT	22 neurologically normal volunteers, some with risk factors for stroke	58	38†	53	20	447	Yes for gray matter, no for white matter
Pantano et al (42)	1984	PET	18 patients without history of cerebral disease or vascular risk factors	38	39†	51	25	461	Yes for gray matter, no for white matter
			9 patients without history of cerebral disease or vascular risk factors	63	34†	42	25	400	NR
Yamaguchi et al (43)	1986	PET	14 healthy volunteers	36	33†	43	21	390	No
			8 healthy volunteers	58	34†	43	24	400	NR
Leenders et al (44)	1990	PET	34 healthy volunteers	45	34†	44*	22	395	Yes for gray matter, no for white matter
Marks et al (9)	1992	2D phase-contrast MR angiography	24 healthy volunteers (n = 14) and patients without ischemic disease (n = 10)	44	NR	NR	NR	858	No
Enzmann et al (18)	1993	2D phase-contrast MR angiography	10 healthy volunteers	29	NR	NR	NR	772	NR
Enzmann et al (12)	1994	2D phase-contrast MR angiography	10 healthy volunteers	29	NR	NR	NR	800	NR

Note.—NR = not reported.
* Number is the calculated mean flow value.
† CBF was calculated on the basis of gray matter and white matter flow values.

To our knowledge, there have been no comprehensive studies in healthy individuals in whom intravascular probes were used to directly measure the flow in the vessels that supply the brain. Thus, the true CBF values in the healthy population are unknown. However, several investigators have assessed CBF in healthy individuals by using minimally invasive or noninvasive indirect methods. In the late 1940s and early 1950s, Kety and Schmidt (21) and others (23–27) calculated CBF by using the concentration of inhaled nitrous oxide in arterial and venous samples taken from the radial artery and the jugular vein in healthy individuals. Later, others used xenon-133 gas and measured the clearance of the injected or inhaled gas in brain regions by using scintillation detectors (30–35) or single photon emission computed tomography (36–38). In the late 1970s, the stable xenon computed tomographic (CT) technique became available. This technique involved sequential scanning of the brain during inhalation of nonradioactive xenon gas, thus allowing CBF measurements within various regions of the brain by observing temporal changes in attenuation (39–41). Later, positron emission tomography (PET) was used for determining regional CBF on the basis of steady-state brain activity during inhalation of oxygen-15–labeled carbon dioxide and molecular oxygen, or O_2 (42–44). In more recent studies (9,12,18), 2D phase-contrast MR angiography has been used in small numbers of patients.

To validate our findings and in the absence of an invasive reference standard for determining the true CBF values in healthy individuals, we correlated our findings with those derived from the investigations mentioned in the preceding paragraph. In most studies (21,23–25,27,30–44), CBF values were reported in terms of milliliters per 100 g of brain tissue per minute. To obtain total CBF values from these studies, the reported values should be multiplied by one one-hundredth of the average weight of the cerebrum. In an analysis of 1,261 adult brains, Ho et al (51) found that the total brain weight varied from 1,201 to 1,349 g in subjects grouped according to age from 85–94 to 25–34 years, respectively. By using these data and correcting for the contribution of the cerebellum to the total brain weight (±10% [50]), we multiplied the reported CBF values by a factor of 10.81–12.14, depending on the mean age in each study group (Table 2). In some of the aforementioned publications (39–44), blood flow values (in milliliters per 100 g of brain tissue per minute) were not given for the entire brain but were determined separately for white and gray matter. In these instances, we assumed a 45% and 55% contribution to brain weight for white matter and gray matter, respectively (52). The results of these calculations are presented in Table 2. In Figure 3, the results of our study together with the calculated total CBF values of the other reported studies are plotted against the mean age of each study group. The values obtained by us and by other investigators show wide ranges of blood flow throughout a given age range and, therefore, the results must be interpreted with caution. Nevertheless, our findings overlap with those of most other studies, which suggests agreement among the results.

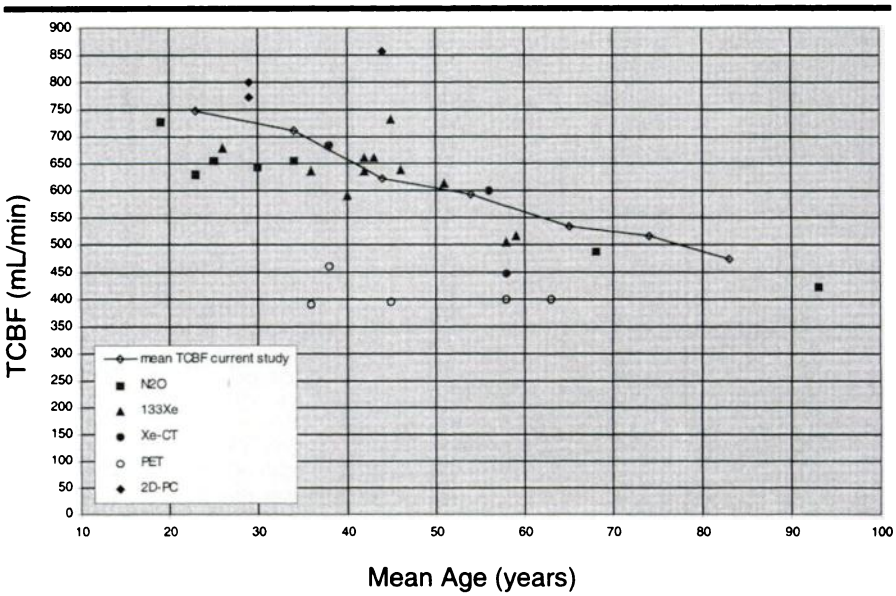

Figure 3. Graph shows mean total CBF (*TCBF*) according to age as measured in the current study and the calculated mean total CBF values according to mean age derived from previous studies in which nitrous oxide inhalation (*N2O*) (21,23-25,27), Xe-133 scintigraphy (*133Xe*) (30-38), xenon CT (*Xe-CT*) (39–41), PET (42–44), and 2D phase-contrast MR angiography (*2D-PC*) (9,12,18) were used.

Some investigators, who evaluated small (n = 8–24) groups of healthy subjects or patients, measured the VFR of the ICA and sometimes of the basilar artery by using 2D phase-contrast MR angiography, most often in combination with cardiac triggering. In these studies, the mean VFR values in relatively young, healthy volunteers ranged from 273 to 337 mL/min for the ICA (12,18,20) and from 161 to 185 mL/min for the basilar artery (12,18), whereas in middle-aged subjects, these values were 251–262 mL/min (14,15,53) for the ICA and 167 mL/min for the basilar artery (53). In two studies (10,13), the VFR for the ICA was measured in a group of older patients with possible carotid stenosis. If the patients who had more than 70% stenosis of the ICA are excluded, the mean VFR values for this vessel were 219 and 214 mL/min. By considering the various age groups in these studies, the mean values for the VFR in the ICA agree well with the values for the young, middle-aged, and older individuals in our study (Table 1). However, the VFR values in the basilar artery in our study were slightly lower than those in other studies. In addition, the mean VFR value of 347 mL/min found in the ICA in one study (9) with relatively old individuals was markedly higher as compared with the results of other 2D phase-contrast MR angiographic studies.

We found a decrease with age of 4.8 mL/min/y in the total CBF. In many of the aforementioned studies (22,29,31–33,35,36,40), the authors also found a decline in total CBF with age. Given an average brain weight of 1,288 g, this decline varied from 1.5 to 4.6 mL/min/y (31–33,35,36). In some studies (30,41,42,44) in which flow was differentiated for gray and white matter, a statistically significant decrease in flow with age was found in gray matter but not in white matter. The authors of other studies (9,25,26,28,38,43,45), however, including some recent ones, were unable to demonstrate a decline in CBF with age. Nevertheless, our results indicate that there is a decrease in blood flow with age

similar to that suggested by the analysis of all data derived from the literature (Fig 3).

Some authors (31,32,36) were unable to demonstrate differences in CBF between sexes, whereas others (54,55) found a higher CBF in women before menopause compared with that in men of the same age. We found no significant sex difference in total CBF for all age groups. In our study, flow was equally distributed between the right and left ICAs within each age group. This has also been found by others (31–33,38,56). However, some studies demonstrated asymmetry, sometimes with left flow dominance (30,36,55) and sometimes with right flow dominance (35,57,58).

A limitation of our study was that not all subjects were free of cerebrovascular disease or risk factors for atherosclerotic disease. However, the aim of this study was to collect VFR values not from a selected population with no disease but from a large group of individuals who can be regarded as a sample of the general population. Analysis of the subgroup of 190 individuals without risk factors or disease revealed a yearly decrease in total CBF of 4.6 mL/min compared with a yearly decrease of 4.8 mL/min for the entire group. Therefore, inclusion of individuals with these risk factors or diseases did not substantially influence the results of this study.

For optimal results in vascular flow measurements with phase-contrast imaging, it is important that the acquisition be performed in a plane perpendicular to the vessel. In our study, the data for these measurements were obtained at the level of the skull base by using an imaging plane positioned as perpendicular as possible to all three of the vessels we investigated. Although at this level, the precavernous portion of the ICA shows little variation in its course, the basilar artery may be tortuous, particularly in older individuals. The resultant obliquity of the vessel with respect to the imaging plane could be a cause of error (4). The results of previous studies (9), however, have shown that slight vessel obliquity does not markedly alter the calculated VFR, because the decrease in apparent average velocity is canceled out by the increase in vessel area.

Another potential problem in the measurement of blood flow with phase-contrast MR images is that the number of pixels within the vessel lumen may be too small to provide accurate results. Previous study results (59) have indicated that at least 16 pixels must cover the cross section of the vessel lumen to yield measurement accuracy to within 10%. Given the in-plane resolution of our technique, the accuracy may be compromised in vessels smaller than 5 mm in diameter. Because the mean diameter of both ICAs was greater than 5 mm in our study, the expected accuracy of the flow measurements was high. Because the mean diameter of the basilar artery was less than 5 mm, however, errors could have occurred during measurement of flow of this vessel. Because the contribution of the basilar artery to total CBF was approximately only 20%, the effect of this potential error in total CBF measurements is likely to be small.

In conclusion, the results of this study suggest that ungated 2D phase-contrast MR angiography can be used as an easy, noninvasive method for determining the VFR of individual blood vessels to the brain. We demonstrated that total CBF declined significantly with age. The results obtained with this technique correlated with those reported by others who used a variety of methods for measuring CBF. Because of its simplicity and speed, ungated 2D phase-contrast MR angiography is well suited for incorporation into a routine imaging protocol.

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