Eur Arch Psychiatr Neurol Sci (1988) 238:33–38

European Archives of Psychiatry and Neurological Sciences

rCBF Landscapes During Motor Performance and Motor Ideation of a Graphic Gesture

Jean Decety[1], **Bernard Philippon**[2], **and David H. Ingvar**[3]

[1]Laboratoire de Neuropsychologie Experimentale, INSERM U94, 16 ave du Doyen Lépine, F-69500 Bron, France
[2]Centre de Médecine Nucléaire, Hopital Cardiologique et Pneumologique Louis Pradel, F-69394 Lyon, France
[3]Department of Clinical Neurophysiology, University Hospital, S-221 85 Lund, Sweden

Summary. The regional cerebral blood flow (rCBF) distribution was measured by ^{133}xenon inhalation using a gamma camera in 18 right-handed volunteers, 6 subjects performing a graphic task (writing numbers in letters) with the right hand, 6 subjects imagining the same task, and 6 subjects were assessed during two rest periods to determine the reproducibility of the technique. The mean rCBF increased between 10% and 25% ($P < 0.01$) during both motor performance and motor ideation. However, there were regional differences. While motor performance activated mainly the rolandic regions bilaterally, motor ideation gave prefrontal and premotor rCBF augmentations. In both situations there was significant bilateral increase in regions corresponding to the cerebellum.

Key words: rCBF – ^{133}Xenon inhalation – Motor ideation – Neuropsychology – Cognitive/motor processes

Introduction

Experimental and clinical studies have shown that reception and perception of sensory messages, as well as motor performance augment the metabolism and blood flow in different parts of the cerebral cortex. It has also been established that functional changes in the cerebral cortex related to mental activity can be demonstrated by measurement of regional cerebral blood flow (rCBF) with ^{133}xenon (Ingvar and Lassen 1975, 1978; Risberg et al. 1975; Risberg 1980, 1986). The rCBF changes recorded are in general interpreted as secondary to regional functional alterations, since there is a coupling between neuronal metabolic activity and the rCBF (Raichle et al. 1976).

The cortical organization of voluntary movement has previously been studied with the intra-arterial rCBF technique by Olesen (1971), Ingvar and Lassen (1975), Ingvar and Philipson (1977), and Roland et al. (1980, 1982, 1985a, 1987). During unilateral voluntary movement, regional activations of cerebral cortex are seen mainly in the contralateral rolandic area. Simple repetitive fingers flexions do not alter the rCBF in the premotor cortex or supplementary motor area (SMA) significantly although complicated sequences of voluntary movements activate the SMA considerably (Roland et al. 1980). In well-trained subjects, the SMA and some anterior cortical regions are selectively activated during motor ideation, i.e. mental simulation of movements (without any actual muscle contractions) (Ingvar and Philipson 1977; Roland et al. 1980). This finding supports the notion that the prefrontal cortex plays a role in the temporal organization of movements and behaviour (Fuster 1980; Ingvar 1985).

Many investigations of so called mental practice (i.e. when one imagines oneself performing a certain motor skill such as throwing a basketball, etc.), have demonstrated its positive effect on motor performance (Feltz and Landers 1983; Denis 1985; Hall and Goss 1985). Mental practice is widely used in sports training. However only few studies (Decety and Mick 1988) have been made of its neurophysiological basis. The main purpose of the present study was to outline further the brain structures which are involved in the cognitive activity underlying motor ideation.

Offprint requests to: J. Decety

On the basis of previous studies (Ingvar and Philipson 1977; Risberg 1980, Roland et al. 1980; Roland and Friberg 1985b) it is advocated that motor ideation like motor performance needs the temporal integrative function of the prefrontal cortex, as well as the SMA and areas which are intimately involved in movement programming.

A specific motor task was used (handwriting) either actually performed or mentally simulated. A graphic task was selected for both neurophysiological and neuropsychological reasons. First, the graphic gesture involves distal segments of the upper extremity which are under controlateral hemispheric motor control. Second, a graphic task should require more of the left hemisphere competence due to its linguistic component. Finally, this task was executed in intra-personal space, according to the distinction made by Roland et al. (1980).

Materials and Methods

The rCBF technique. A double-headed gamma camera (rota camera Siemens) equipped with low resolution (15 mm) and high efficiency collimators was used to measure rCBF over a period of 2 min after 1.5 min inhalation of ^{133}xenon. The inhaled gas mixture contained approximatively 75 MBq/l at the first measurement and 150 MBq/l at the second measurement. Each collimator was positioned perpendicular and parallel to the sagittal axis of the brain as tightly as possible to subject's skull.

An Initial Slope Index (ISI 2 min) was the parameter examined. Calculation of ISI was made using the mono-compartmental analysis method described by Fox and al. (1985), derived from the method of Obrist et al. (1975), with a correction for $PaCO_2$.

The rCBF was measured and visualized both in ml/min per 100 g and as a percentage of the variation between rest and activity in each subject. Calculated values of ISI (min^{-1}) were corrected by the partition coefficient relative to the grey matter 0.85 g/ml). No other correction was made according the correlation known between the ISI and the total cerebral blood flow. Regional variations were calculated as a percentage (rCBF2-rCBF1/rCBF1 × 100) of the hemispheric mean.

Subjects. A total of 18 neurologically normal subjects (undergraduates) were investigated (8 females and 11 males). Their ages ranged between 20 and 28 years. Their ability in motor ideation was assessed by Sheehan's questionnaire (1967) and the Movement Imagery Questionnaire (Hall and Pongrac 1983). All were classified as high imagers. Their right handedness (LQ > 85) was assessed according to the Edinburgh Handedness Inventory (Oldfield 1971). Each subject gave informed consent according to the Declaration of Helsinki.

Procedure. The subjects were randomly divided into three groups, and two rCBF measurements separated by a 15 min interval were performed.

(1) Six subjects were assessed during two rest periods in order to estimate the reproducibility of the rCBF method.

(2) Six further subjects were studied first at rest, then during an imagined graphic task with the dominant right hand.

(3) Finally, six subjects were studied at rest and then during the actual performance of the graphic task with the dominant right hand.

In all conditions (rest, actual, mental) the subjects were seated in a reclined position, with ears plugs and blindfolded in order to minimize external stimuli. In the rest condition they were asked to avoid any kind of specific mental activity.

The graphic task (actual or mental) consisted of writing a series of numbers in letters (one, two... etc.) with a pen on a sheet of paper. Verbal instructions were given for both the actual and mental graphic task about 10 min before the beginning of the task.

During the mental simulation, the subjects were told to imagine feeling themselves writing the numbers (in letters: one, two, three...) with the right hand (imagery at the first person perspective). They were required to start with the number one at a brief external signal (tactile) and continue writing until a final signal (tactile) given by the experimentator on the contralateral hand after 5.40 min. At the end the subjects were asked to report how many numbers they had imagined writing. Usually, the subjects arrived at "fifty-eight" (SD 10.5). The same procedure was followed during the actual graphic performance, except that the subjects actually wrote the numbers on a sheet of paper, and arrived at "sixty-seven" (SD 11.7).

Data Processing. Brain regions of interest were drawn on the video screen of the computer with a joystick, mainly using Roland's (1985b) map of the human cerebral cortex obtained with a 254 detector camera and the intra-carotid ^{133}xenon method. A control was created using a human brain atlas. An outline of each hemisphere was drawn from Magnetic Nuclear Reasonance pictures of two subject's brains which were selected as having the mean head size of the whole group. With this gross technique it was possible to divide each hemisphere into 9 areas (Figs. 1 and 2).

Results

Reproducibility

The intra-subject variability for the 9 brain regions choosen was calculated for the hemispheric mean cerebral blood-flow, listed separately for the left and the right side and for the first and second rest measurements, respectively (Table 1).

No statistical differences were found between the left and the right hemisphere regions during the first rest test or during the second test. This was found for both hemispheres ($P > 0.90$). No significant intra-hemispheric regional differences were found ($P > 0.50$). The $PaCO_2$ was very stable with no significative variations.

The rCBF values obtained at rest II were compared to the values from rest I and expressed as percentage variation as shown in Table 1. The variations were limited and equivalent to the intra-subject variability obtained by Blauenstein et al. (1977). The inter-subject coefficients of variation ranged between 1.9% and 9.6%. The intra-hemispheric coefficients of variation within each subject ranged between 1.6% and 5.18%.

Table 1. Mean values ($\bar{x}$), SDs and coefficients of variation (CV) of the regional cerebral blood flow (rCBF) (ml/min per 100 g) in 9 cortical regions in six normal subjects during rests I and II

	Rest I				Rest II			
	RH		LH		RH		LH	
	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD
Area 1	52.73	(4.5)	53.21	(5.1)	54.51	(4.3)	53.09	(4.4)
Area 2	52.46	(3.6)	54.80	(5.8)	46.63	(3.6)	53.84	(4.6)
Area 3	54.27	(3.8)	56.07	(4.61)	56.67	(4.5)	57.09	(3.5)
Area 4	54.38	(4.9)	54.52	(5.4)	56.58	(3.1)	52.72	(3.3)
Area 5	55.17	(4.2)	54.31	(4.1)	56.84	(3.3)	54.80	(5.4)
Area 6	52.5	(4.2)	52.82	(4.7)	52.8	(3.9)	53.70	(5.4)
Area 7	54.72	(5.2)	54.29	(3.3)	55.17	(3.4)	56.23	(4.8)
Area 8	52.0	(4.2)	51.15	(5.5)	52.35	(5.7)	51.52	(4.4)
Area 9	53.84	(4.6)	54.17	(4.5)	55.68	(3.4)	53.86	(3.6)
HCBF	53.1	(4.7)	53.70	(4.5)	54.80	(3.2)	53.47	(4.1)
CV (%)	2.15		2.58		6.00		3.1	

HCBF: Hemispheric cerebral blood flow; RH: right hemisphere; LH: left hemisphere
PCO_2: 5.6% SD 0.79 at rest I; 5.5% SD 0.80 at rest II

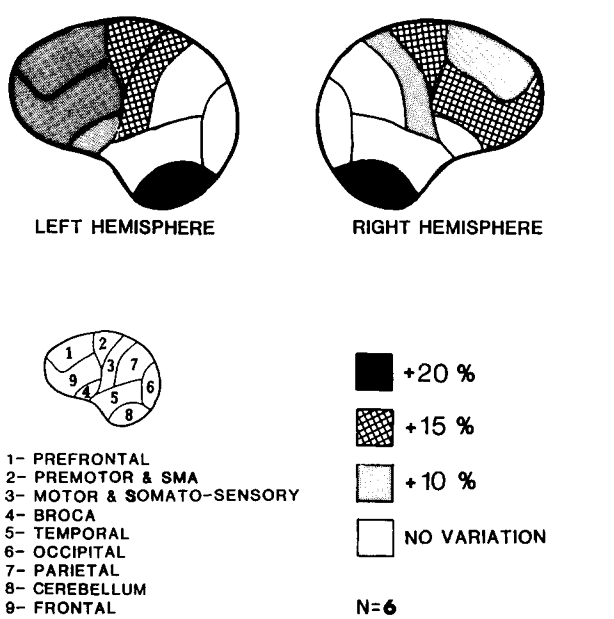

Fig. 1. rCBF variations in percent, calculated between rest and an actual graphic task (handwriting). Left and right hemispheres of six subjects

Graphic Performance

During the right hand graphic task the rCBF increased bilaterally in the prefrontal region (> 10%), the SMA (> 15%) and in the regions corresponding to the cerebellum (> 20%). The Broca region was activated only in the left hemisphere (> 10%). These results are illustrated in Fig. 1. The t values were calculated between regional values of percentage variation during motor performance (actual) in six subjects and regional reproducibility values in six subjects as shown in Table 2. No regional differences were found between right and left hemisphere (> 0.10).

Graphic Ideation

The rCBF augmentations during motor ideation (graphic task) were located bilaterally, in the prefontal region (> 10%), the premotor and SMA areas (> 15%) and also in regions corresponding to the cerebellum (> 15%), as illustrated in Fig. 2. The t values were calculated between regional values of percentage variation during motor ideation in 6 subjects and regional reproducibility in 6 subjects values as shown in Table 2. No regional statistical differences were found between the mean flow of the two hemispheres and between the mean hemispheric blood flow at rest and during either the actual or the mental risk. Hence, cerebral blood flow variations were only regional (Table 3).

Discussion

It should be emphasized that the present rCBF technique (gamma camera) proved suitable for demonstration cerebral events accompanying motor ideation. The low variation in regional flow values between

Table 2. Regional *t*-test results calculated as a percentage of the variation between rest and actual performance or motor ideation in 9 cortical areas of both cerebral hemispheres

Area	Actual ($n=6$)		Mental ($n=6$)		Reproducibility ($n=6$)	
	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD
LH	13.6	(3.9)**	14.2	(3.9)**	0.3	(2.3)
1 – Prefrontal						
RH	12.4	(6.4)*	8.7	(1.9)*	2.4	(1.0)
LH	19.7	(4.2)**	16.7	(5.1)***	1.6	(2.3)
2 – Premotor and supplementary motor area (SMA)						
RH	16.9	(6.2)***	11.8	(3.3)**	3.7	(2.4)
LH	15.3	(3.5)**	0.2	(3.4)	1.9	(1.9)
3 – Motor and somatosensory						
RH	10.9	(5.1)*	1.2	(2.3)	3.8	(1.4)
LH	14.3	(5.3)*	4.5	(3.8)	0.8	(1.7)
4 – Broca						
RH	3.1	(5.5)	4.2	(5.0)	4.1	(2.8)
LH	8.9	(3.8)	1.4	(4.7)	0.5	(2.9)
5 – Temporal						
RH	6.2	(6.1)	4.2	(5.5)	1.9	(3.8)
LH	2.6	(1.8)	2.4	(3.1)	1.9	(2.3)
6 – Occipital						
RH	1.5	(2.2)	0.0	(4.7)	1.5	(2.5)
LH	2.9	(3.5)	−5.5	(2.2)	4.3	(2.9)
7 – Parietal						
RH	0.8	(2.5)	−3.8	(0.7)	0.7	(2.1)
LH	24.1	(9.0)***	17.8	(4.8)***	1.0	(2.8)
8 – Cerebellum						
RH	23.8	(4.9)***	18.0	(3.5)***	0.6	(2.5)
LH	9.8	(4.2)	6.6	(6.1)	0.1	(3.5)
9 – Frontal						
RH	13.5	(5.4)	6.5	(4.7)	3.8	(4.8)

Mean rCBF changes as a percentage of the variation
LH: Left hemisphere; RH: right hemisphere
*** $P<0.001$; ** $P<0.01$; * $P<0.02$ (*df:* 10)

two rest conditions demonstrated the relability of the technique.

Unfortunately, our technique did not provide any tomographic information. In spite of this point, these results fit into the hypothesis that mental imagery of movement involves some anatomical structures participating in the early stages of motor function (MacKay 1981; Decety and Mick 1988) and support an "outflow explanation" of mental simulation of movement (Kohl and Roenker 1983). The findings confirm the observation of Ingvar and Philipson (1977) of the focal distribution of cerebral blood flow in the dominant hemisphere during motor ideation. The task was to imagine a slow and rhythmic clenching movement of the right hand. The increase was most marked in premotor and frontal regions.

This study also supports a recent rCBF and rCMRO2 PET'study by Roland and al. (1987) in which subjects imagined walking and turn alternatively to the left and to the right. This mental task required knowledge of relations in extra-personal space and retrieval of visual information from memory whereas the mental graphic task used in our experiment did not. This might explain why no rCBF variations were found in the parietal cortex.

A new finding was the large increase observed in the regions corresponding to the cerebellum during both motor performance of the graphic gesture and

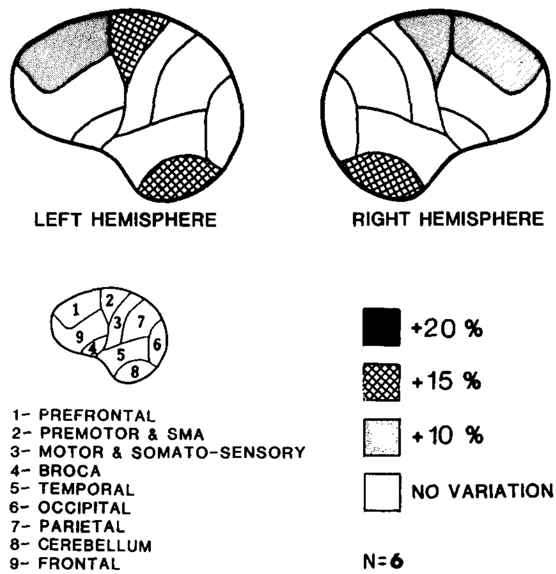

Fig. 2. rCBF variations in percent, calculated between rest and motor ideation of a graphic task (handwriting). Left and right hemispheres of six subjects

Table 3. Mean hemispheric blood flow *($\bar{x}$)* and SD in rest condition and an actual or a mental graphic task. The values are in ml/min per 100 g

	Contralateral		Ipsilateral		*n*
	$\bar{x}$	SD	$\bar{x}$	SD	
Rest	54.5	(4.6)	55.5	(3.8)	12
Actual task	56.4	(2.5)	57.1	(2.6)	6
Mental task	54.4	(6.3)	54.2	(4.8)	6

its mental simulation. This might be related to some motor planning activity, or motor simulation since many prefrontal areas, activated during motor activities as well as during motor imagery, project to the cerebellum. These close connections suggest that the cerebellum participates in the formation and subsequent execution of motor programs (Ito 1984). The SMA has a wide range of connectivity both in giving and in receiving (Eccles 1982). The efferent and afferent connections of the SMA, studied in monkeys, also support the possible role that the SMA plays in the voluntary planning of motor actions (Jürgens 1983). It is interesting to observe that these findings demonstrate the involvement of both prefrontal cortex including the SMA and the cerebellum in motor ideation. Hence, motor ideation may share with actual motor behaviour some neural/cognitive processes. This might help to explain the positive effect of mental practice in motor skill performance.

Acknowledgements. This work was supported in part by a regional Biomedical engineering contract (GBM No 50 1985/09) from the Centre National de Recherches Scientifiques, Paris.

Parts of this work were presented at the 11th European Conference of the International Neuropsychological Society, Lahti, University of Helsinki, Finland, July 1988.

References

Blaunstein UW, Halsey JH, Wilson EM, Wills EL, Risberg (1977) ^{133}Xenon inhalation method. Analysis of reproducibility: some of its physiological implications. Stroke 177: 92–101

Decety J, Mick G (1988) Mental imagery of movement and motor performance: neuro-cognitive approach and practical interest. Medecine et Sport (in press)

Denis M (1985) Visual imagery and the use of mental practice in the development of motor skills. Can J Appl Sports Sci 10:4s–16s

Eccles JC (1982) The initiation of voluntary movements by the supplementary motor area. Arch Psychiatry Neurol Sci 231:423–441

Feltz DL, Landers DM (1983) The effects of mental practice on motor skill learning and performance: a meta analysis. J Sport Psychol 5:25–57

Fox RA, Knuckey RF, Fleay RF, Stokes Bar, van der Shaaf A, Surveyor I (1985) Regional cerebral blood flow utilising the gamma-camera and xenon inhalation: reproducibility and clinical applications. Stroke 16:1010–1015

Fuster JM (1980) The prefrontal cortex. Raven Press, New York

Hall CR, Goss S (1985) Imagery research in motor learning. In: Goodman D, Wilberg RB, Franks IM (eds) Differing perspectives in motor learning, memory and control. Elsevier Science Publisher, Amsterdam

Hall CR, Pongrac J (1983) Movement imagery questionnaire. University of Western Ontario, London-Canada

Ingvar DH (1985) Memory of the future: and essay on the temporal organisation of conscious awareness. Hum Neurobiol 4:127–136

Ingvar DH, Lassen NA (1975) Brain work: The coupling of function, metabolism and blood flow in the brain. Munksgaard, Copenhagen

Ingvar DH, Lasssen NA (1978) Cerebral function, metabolism and blood flow. Acta Neurol Scand 57:262–269

Ingvar DH, Philipson L (1977) Distribution of cerebral blood flow in the dominant hemisphere during motor ideation and motor performance. Ann Neurol 2:230–237

Ito M (1984) The cerebellum and neural control. Raven Press, New York

Jürgens U (1983) The efferent and afferent connections of the supplementary motor area. Brain Res 300:63–81

Kohl RM, Roenker DL (1983) Mechanisms involvement during skill imagery. J Motor Behav 15, 2:179–190

MacKay DJ (1981) The problem of mental practice. J Motor Behav 13(4):274–285

Obrist WD, Thompson HK, Hsioh Shan Wang Jr, Wilkinson WE (1975) Regional cerebral blood flow estimated by ^{133}xenon inhalation. Stroke 6:45–256

Olesen J (1971) Controlateral focal increase of cerebral blood flow in man during arm work. Brain 94:635–646

Oldfield RC (1971) The assessment and analysis of handedness: The Edinburgh inventory. Neuropsychologia 9:97–113

Raichle ME, Grubb RL, Gabo MH, Eichling JO, Ter-Pogossian MM (1976) Correlation between regional cerebral blood flow and oxidative metabolism: in vivo studies in man. Arch Neurol (Chicago) 33:523–526

Risberg J, Halsey JH, Willis EL, Wilson ED (1975) Hemispheric specialization in normal man studied by bilateral measurements of the regional cerebral blood flow. Brain 98:511–524

Risberg J (1980) Regional cerebral blood flow measurements by ^{133}Xe inhalation: methodology and applications in neuropsychology and psychiatry. Brain Lang 9:9–34

Risberg J (1986) Regional cerebral blood flow in neuropsychology. Neuropsychology 24:135–140

Roland PE, Larsen B, Lassen NA, Skinhoj E (1980) Supplementary motor area and other cortical areas in organization of voluntary movements in man. J Neurophysiol 42:118–136

Roland PE, Meyer E, Shibasaki T, Yamamoto YL, Thompson CJ (1982) Regional cerebral blood flow changes in cortex and basal ganglia during voluntary movements in normal human volunteers. J Neurophysiol 48:467–480

Roland PE (1985a) Cortical organization of voluntary behavior in man. Hum Neurobiol 4:155–167

Roland PE, Friberg L (1985b) Localization of cortical areas activated by thinking. J Neurophysiol 53:1219–1243

Roland PE, Eriksson L, Stone-Elander S, Widen L (1987) Does mental activity change the oxidative metabolism of the brain? J Neurosci 8:2373–2389

Sheehan PW (1967) A shortened form of Betts' questionnaire upon mental imagery. J Clin Psychol 23:386–389

Received May 16, 1988