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Review article

Reference values for resting blood flow to organs of man

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Abstract. The lack of a reliable quantitative description of blood flow in man has hampered the development of accurate biokinetic models of essential elements, drugs, imaging agents, and carcinogens. In this paper we review and analyse data on blood flow and identify representative percentages of cardiac output and absolute blood flow rates to organs and tissues of man for use as reference values for biokinetic models. To keep the review and analysis to a manageable size we have limited attention to the resting state and have suggested reference values for absolute and relative flow rates only for adult males and females.

Contents

1. Introduction

Biokinetic models of essential elements, drugs, or environmental contaminants in man often require a detailed estimate of the distribution of cardiac output, particularly when there is

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a need to describe the early systemic distribution of the substance (Price *et al* 1959, Cowles *et al* 1971, ICRP 1988, Leggett and Williams 1988). Although several tabulations of blood flow to organs are available, none of these appear to have been based on a large or representative portion of the available data on man or on consistent normalisation techniques. As illustrated in table 1, flow rates given in different tabulations often differ by 50-300% even for some of the major organs and tissues.

Table 1. Blood flow rates (ml per kg tissue per min) to tissues of resting man, as given in some reviews and physiology texts.

Tissue	Mapleson 1963[a]	Bell *et al* 1968[b]	Cowles *et al* 1971[c]	Brobeck 1979[d]	Ganong 1979[e]	Guyton 1982[f]
Adipose tissue	20	–	24	–	–	–
Adrenals	5000	–	5100	–	–	1800
Bone	0	120	0	–	–	50
Brain	510	650	530	540	540	500
Lung tissue	–	–	–	570	–	180
Heart tissue	800	1000	810	700	840	610
Intestines	–	700	390	540	–	700
Kidneys	4100	1500	4000	4300	4200	3600
Liver (total)	410	1500	840	540	580	750
Red marrow	90	–	400	–	–	–
Skeletal muscle	20-50	20	21	27	27	26
Skin	20-50	30	57	–	130	120
Spleen	–	400	390	–	–	700
Thyroid	4000	5600	5000	–	–	2500

[a] From table 1, p 198; see discussion of muscle and skin on p 199.
[b] From table 27.30, p 600, and discussions on pp 270, 618, 932.
[c] From table 1, p 524, assuming total liver flow equals total splanchnic flow and assigning flow rate for 'splanchnic tissue' to intestines and spleen.
[d] From table 3.16, p 3-126; flow to lung tissue from figure 3.1, p 3-4.
[e] From table 32-1, p 467.
[f] From table 16-1 and discussion on p 221, using organ weights for reference male, this paper.

The purposes of this paper are: (1) to provide a review and consistent distillation of data related to the distribution of cardiac output in man, and (2) to identify representative percentages of cardiac output and absolute blood flow rates to organs of man for use as reference values for biokinetic models. To keep the review and analysis to a manageable size we have limited attention to the resting state and have suggested reference values for blood flow only for adult males and females. In a later study we will consider variation in blood flow to organs as a function of age and activity.

2. Methods

2.1. Compilation and reduction of data

The initial tasks were: (1) compilation of reported blood flow rates for man and laboratory animals, and (2) transformation of relevant blood flow data to estimates of the percentage of cardiac output (PCO) going to a given organ or tissue of the human body. As far as practical, attention was restricted to data for young or middle-aged adult humans described as healthy and/or control subjects. Grouped data were usually excluded if a substantial portion of the subjects appeared to be outside the age range 18-50 y. For some infrequently studied organs it was necessary to consider data for very old or seriously ill persons or for

laboratory animals. Among animal studies, preference was given to studies of primates and other relatively large experimental animals such as sheep, pigs, dogs, and goats. Also, preference was given to fairly comprehensive animal studies that permitted comparisons of reported blood flow for several organs with compiled data for man, thus allowing an evaluation of the best means of extrapolating data from a given species to man. For example, one may assume that absolute flow rates in ml kg^{-1} min^{-1} are the same in both species or, alternatively, that PCOs to certain organs are the same. We generally used the assumption that gave best agreement overall for the organs that have been frequently studied in man.

From each selected study on man or laboratory animals we determined at least one 'study value' for the organ or tissue of interest, that is, a representative value of the PCO going to that organ or tissue based on data for all subjects of the study or some distinct subgroup (for example, all control subjects or all healthy male subjects). Most subjects of studies on human blood flow have been adult males, but some studies have included a sufficient number of subjects of both sexes to allow determination of separate study values for males and females.

In some studies of regional blood flow, the cardiac output (CO) of each subject was also measured, thus allowing straightforward determinations of study-specific PCOs to the investigated regions. In most cases, however, the PCO to an organ or tissue could be derived only by relating reported blood flow rates, given either as total flow to an organ in units

Table 2. Organ masses (g) in reference adult male and female.

Organ or tissue	Male	Female
Adipose tissue*	12500	17500
Adrenal glands	14	14
Brain	1400	1200
Gastrointestinal tract	1200	1130
Stomach and oesophagus	190	170
Small intestine	640	600
Upper large intestine	210	200
Lower large intestine	160	160
Heart	330	270
Kidneys	310	275
Liver	1800	1400
Lymph nodes	250	200
Lungs	470	370
Muscle (skeletal)	30000	18000
Pancreas	100	85
Salivary glands	85	70
Separable connective tissue	1600	1270
Skeleton	10500	8500
Skin	3300	2300
Spleen	180	150
Spinal cord with fluid	150	130
Thyroid	20	17
Tongue	70	60
Urinary bladder	45	45
Blood	5900	4100
Gastrointestinal tract contents	1005	1005
Remainder	1771	1909
Total	73000	60000

*Includes only subcutaneous and other separable adipose tissue.

such as ml min^{-1} or as a perfusion rate of tissue in units such as ml kg^{-1} min^{-1}, to a reference CO and reference organ masses. If the age, sex, and/or body size of each subject or group of subjects was known, then appropriate adjustments in organ masses and COs could be made. For this purpose we defined reference adult male and female subjects.

Organ masses for reference 35 year old male and female humans are given in table 2. These values were based primarily on reference organ masses given in Publication 23 of the International Commission on Radiological Protection (ICRP 1975). The most important departures from the ICRP reference values are the following: (1) total body mass was increased from 70 to 73 kg for the male and from 58 to 60 kg for the female, in agreement with data for the young to middle-aged subjects considered in this study, in Altman and Dittmer (1972), and in a recent review of the literature on cardiac output and blood volume (Williams 1990); (2) the mass of the skeleton was increased in both sexes based on data of Borisov and Marei (1974) (see also Williams and Leggett 1987); (3) the mass of skeletal muscle was increased in both sexes (Malina 1986, Williams and Leggett 1987); and (4) the mass of skin was increased in both sexes, based on a recent unpublished review by G D Kerr prepared as part of the forthcoming revision of ICRP Publication 23.

When COs of subjects were not determined by the original investigators, estimated total blood flow to an organ was converted to a PCO using reference age, sex, and size-specific values for CO as suggested in a recent review (Williams 1990). If no age or body size was given, then the reference CO for a 35 year old person of average size was used (6700 ml min^{-1} for a supine, 73 kg male with a body surface area of 1.88 m^2, and 5800 ml min^{-1} for a supine, 60 kg female with a body surface area of 1.62 m^2). If subjects were sitting or standing, reference CO values for the supine position were reduced by 20% (Williams 1990). In some cases our study value differs from the PCO estimated in the original study because of different reference values used for CO, organ masses, or other quantities not determined for the subjects of the study.

2.2. Selection of reference values from compiled study values

We suspect that experimental errors and differences in experimental techniques and assumptions from one study to another are often the primary sources of variability among study values for a given organ, but biological variability among subjects and/or study groups must also be considered. In the selection of reference PCOs we considered five different estimates or measures of the central tendency of the distributions indicated by all tabulated values or all values applicable to a given sex. Some of these measures weight study values according to the number of subjects in each study and others give equal weight to each study value. The five measures are as follows:

1. the median of study values;
2. the median of study values with each study value repeated according to the number of subjects of that study;
3. the weighted mean of study values, with the weights being the number of subjects in each study;
4. the unweighted mean of study values;
5. the weighted trimmed mean for all studies and all subjects, as defined by Williams and Leggett (1987). Briefly, one trims off the highest 20% and lowest 20% of study values and takes the weighted mean of remaining values, with weights being the number of subjects of remaining studies. Study values determined for non-humans or for an unknown number of human subjects are given a weight of one. If fractions of studies are left at the top and bottom as a result of trimming (e.g., given 21

studies, 4.2 studies would be trimmed off each end), the weight of an end study is the number of subjects of the study multiplied by that fraction (0.8 in this example).

When these five values were in close agreement, their median value was taken as a first estimate of the typical PCO to the given organ or tissue of males, females, or both sexes, depending on the data set. When the various measures of central tendency were not in close agreement, additional factors were considered as described later for individual organs. In the following the median of these five measures is referred to as the 'provisional measure of central tendency' (PMCT), and for brevity only the PMCT and range of the five measures are given. While the derivation of a PMCT provides a reasonably objective scheme for obtaining a first estimate of the PCO flowing to an organ, it should be cautioned that this scheme cannot override the need for scientific judgment in many cases. This becomes evident in the following section in the descriptions of selections of reference PCOs.

Reference PCOs to all organs and tissues were required to sum to 100%. After first estimates of typical PCOs to all organs had been derived, we reassessed reported data, reference organ masses, and other quantities and assumptions used to determine study values, in order to determine the most likely sources of a total overestimate of about 2% for the male and a total underestimate of about 4% for the female. This led to some apparent improvements in study values and resulting estimates of typical PCOs, but a few small, arbitrary adjustments of first estimates (within their ranges of uncertainty) were required to achieve an exact balance.

The tracer and/or technique associated with each study value is given in abbreviated form in the tables of study values. Analysis of the dependence of estimates of the PCO to an organ or tissue on the tracer and/or technique has been carried out whenever feasible. For descriptions and critical comparisons of alternative methods for measurement of organ blood flow the reader is referred to Wade and Bishop (1962), Harris and Heath (1977), Granger and Bulkley (1981), Renkin and Michel (1983, 1984), Tothill (1984) and Bernstein (1985).

3. Selection of reference values

3.1. Brain

Blood flow to brain has been quantified more precisely than flow to other organs, with most estimates of PCO to brain falling between 10 and 16% (table 3). Estimates have been based on several methods, most commonly by measurement of uptake of nitrous oxide and other inert gases. Study values based on positron emission tomography (PET) were substantially lower on average than those based on other techniques and were omitted from table 3; otherwise, no systematic differences with technique were identified. There is a decline with age in absolute blood flow to the brain (Fazekas *et al* 1952, Bernsmeier and Siemons 1953, Scheinberg *et al* 1953, Gordon 1956), but the fraction of CO going to the brain appears to fall little if at all throughout adult life. Most reported values are for males where sex is listed, but results of those studies involving both males and females indicate that the absolute blood flow per gram of brain tissue and the PCO to brain may not differ substantially with sex (Shenkin *et al* 1953, Lassen and Munck 1955, Perlmutter *et al* 1987).

The PMCT for all study values in table 3 is 11.4% (the range of all five measures of central tendency is 11.1-11.9%) and for values based only on male subjects is 11.7% (11.4-12.2%). We have selected 12% as the reference PCO to brain for adult males and females. (Reference PCOs are expressed as two digits and as a multiple of 0.5% of CO.)

Table 3. Estimates of the PCO to brain, based on reported measurements on humans with apparently normal cerebral circulation and cardiac function.

% CO	Reference	Method of measurement	Number of subjects	Subject characteristics
20.4	Kety and Schmidt (1946)	N_20	7	males, 23-31 y
15.3	Reinmuth *et al* (1965)	Iodine	32	
15.2	Lewis *et al* (1960)	Kr and N_2O	10	young adult males
14.9	Zobl *et al* (1965)	N_2O	13	avg. age 34 y
14.8	Lavender *et al* (1981)	Microspheres	7	
14.0	Sokoloff *et al* (1955)	N_2O	13	males, 20-34 y
13.2	Lantz *et al* (1981)	Video dilution	29	
12.8	Scheinberg and Stead (1949)	N_2O	20	males, 18-36 y
12.5	Nylin *et al* (1956)	Th-labelled RBC	11	
12.2	Scheinberg *et al* (1953)	N_2O	32	males, 38-79 y
12.2	Bernsmeier and Siemons (1953)	N_2O	30	17-64 y
12.0	Shenkin *et al* (1953)	N_2O	3	males, avg. age 32 y
11.8	Crumpton and Murphy (1952)		6	
11.7	Kleinerman and Sancetta (1955)	N_2O	10	
11.5	Lassen *et al* (1983)	Iodine	2	
11.5	McHenry (1964)	Kr	25	males, 18-57 y
11.4	Nylin *et al* (1961)	P-labelled RBC	10	males, 26-46 y
11.4	Shapiro *et al* (1966)	N_2O	6	21-37 y
11.4	Dewar and Davidson (1958)	N_2O	6	males, 21-24 y
11.4	Lassen and Klee (1965)	Kr	11	males, 23-83 y
11.3	Fazekas *et al* (1952)	N_2O	9	avg. age 34 y
11.1	Mangold *et al* (1955)	N_2O	11	males, avg. age 22 y
11.1	Novack *et al* (1953)	N_2O	12	under age 40
11.0	Kety and Schmidt (1948)	N_2O	14	males, 23-31 y
10.9	Lassen *et al* (1977)	Xe	49	
10.7	Lassen and Munck (1955)	Kr	10	males, 17-55 y
10.6	Heyman *et al* (1953)	N_2O	25	avg. age 29 y
10.6	Patterson *et al* (1955)	N_2O	23	19-53 y
10.6	Lassen and Munck (1955)	Kr	10	females, 25-54 y
10.6	Gordon (1956)	N_2O	88	20-50 y
10.4	Munck and Lassen (1957)	Kr	9	males, 26-67 y
10.4	Patterson *et al* (1951)	N_2O	8	
10.4	Ingvar *et al* (1965)	Xe	7	young adult males
10.3	Shenkin *et al* (1953)	N_2O	9	females, avg. age 29 y
10.2	Wyper *et al* (1976)	Xe	37	
10.2	Kleinerman and Sokoloff (1953)	N_2O	8	
10.1	Heyman *et al* (1952)	N_2O	10	avg. age 31 y
9.4	Alexander *et al* (1968)	Kr		adults
8.6	Crean *et al* (1986)	Microspheres	8	males, 27-67 y

3.2. Kidneys

There have been numerous estimates of the rate of plasma flow to kidneys, most often based on clearance of *p*-aminohippurate (PAH) or diodrast. Clearances of PAH and diodrast (or diodone) were converted to renal plasma flow using extraction fractions provided by the original investigators or typical fractions indicated by data of Maxwell *et al* (1950), Smith (1958), and Wesson (1969). For conversion of renal plasma flow to renal blood flow we assumed a haematocrit of 45% for males and 40% for females (Wesson 1969, ICRP 1975, Brobeck 1979), except where haematocrit was determined by the original investigators.

The PCO to kidneys diminishes with advancing age and may also be decreased in persons with hypertension or chronic heart disease (Wade and Bishop 1962). The estimated renal

Table 4. Estimates of the Qco to kidneys, based on reported measurements on normotensive human subjects with apparently normal renal and cardiac functions.

% Qco	Reference	Method of measurement	Number of subjects	Subject characteristics
22.9	Aas and Blegen (1949)	PAH	3	males, 26-46 y
22.7	Friedman *et al* (1941)	diodrast	6	males, 22-50 y
21.6	Radigan and Robinson (1949)	PAH	5	males
21.4	Talbott *et al* (1942)	diodrast	3	males, 18-54 y
21.3	Edelman *et al* (1950)	PAH	8	males, avg. age 34 y
21.3	Smith (1958)	diodrast	67	males, 16-60 y
21.1	Lee *et al* (1966)	PAH	7	males, avg. age 24 y
21.0	Kirkendall *et al* (1959)	PAH	25	avg. age 31 y
21.0	Miles *et al* (1952)	PAH	9	males, avg. age 38 y
21.0	Goldring *et al* (1940)	diodrast	43	adult male patients
20.6	Ladefoged and Pedersen (1967)	Xe	6	males, 23-27 y
20.2	Sirota *et al* (1950)	PAH	10	males, 20-49 y
20.1	De Wardener and McSwiney (1951)	PAH	3	males
19.9	Wiggins *et al* (1951)	PAH	2	males, 36 and 43 y
19.8	Chasis *et al* (1945)	PAH	11	males
19.7	Heller and Jacobson (1950)	PAH	8	males, 20-45 y
19.7	Cargill (1949)	PAH	10	
19.2	Edelman *et al* (1950)	PAH	4	females, avg. age 39 y
19.1	Mokotoff *et al* (1948)	PAH	4	females, 23-45 y
19.0	Barclay *et al* (1947a)	diodone	13	males, 20-24 y
19.0	Lewis *et al* (1952)	PAH	7	males, 24-42 y
19.0	Crosley *et al* (1956)	N_2O	5	males, 21-37 y
19.0	Bucht (1949)	PAH	3	females, 29-51 y
18.9	Brun *et al* (1947b)	PAH	8	males, 23-27 y
18.9	Davies and Shock (1950)	diodrast	28	males, 20-50 y
18.9	Aurell *et al* (1966)	PAH	13	males, 24-43 y
18.8	Fishman *et al* (1951)	PAH	2	males, 21 and 52 y
18.7	[a]Foa (1942)	diodrast	7	males, 22-56 y
18.6	Thomasson (1957)	PAH	11	males, 19-40 y
18.5	Lauson *et al* (1944)	PAH	4	males, 42-62 y
18.5	Avasthi *et al* (1987)	ultrasound	5	adults, avg. age 28 y
18.3	Talbott *et al* (1942)	diodrast	2	females, 23 and 32 y
18.3	Kolberg (1959)	PAH	2	males, 36 and 45 y
18.2	Aas and Blegen (1949)	PAH	6	females, avg. age 36 y
18.1	Mokotoff *et al* (1948)	PAH	10	males, 22-40 y
18.1	Ikkos *et al* (1956)	PAH	11	males, 21-56 y
18.0	Barclay *et al* (1947b)	diodone	10	students (9 males)
18.0	Bolomey *et al* (1949)	PAH	13	males aged 29-62 y
17.9	Nickel *et al* (1954)	PAH and diodrast	8	males, 17-48 y
17.8	[a]Findley (1942)	diodrast	17	males, under 40 y
17.7	Bradley and Halperin (1947)	PAH	5	
17.6	Brun *et al* (1947a)	diodrast	10	males, 21-25 y
17.4	[b]Merrill (1945)	PAH	35	
17.4	Reubi *et al* (1973)	ind. dilution	8	
17.3	Maxwell and Breed (1951)	PAH	18	males, 20-66 y
17.3	Wesson (1964)	PAH	8	males, 27-43 y
17.3	Werko *et al* (1952)	PAH	50	
17.2	Chasis *et al* (1945)	PAH	8	females
17.2	Lauson *et al* (1944)	PAH	2	females, 21 and 48 y
17.2	Foa and Foa (1942)	diodrast	5	females, 23-58 y
17.2	[a]Friedman (1941)	diodrast	5	females, 25-40 y
17.1	Goldring *et al* (1940)	diodrast	11	females, avg. age 32 y
17.1	Smith (1958)	diodrast	17	females, 16-55 y

17.0	Kolberg (1959)	PAH	4	females, 26-46 y
17.0	Hollenberg *et al* (1969)	Xe	36	23-69 y
17.0	Smythe *et al* (1952)	PAH	10	females, 18-37 y
16.9	Grimby (1965)	PAH	15	males, 21-44 y
16.9	Chapman *et al* (1948)	PAH	9	males, 21-32 y
16.9	Friedman *et al* (1941)	diodrast	5	females, 25-40 y
16.8	Pfeiffer *et al* (1950)	PAH	4	males
16.8	Brun *et al* (1947a)	diodrast	10	females, 19-27 y
16.7	Culbertson *et al* (1957)	PAH	9	males, 15-44 y
16.6	Smythe *et al* (1952)	PAH	8	males, 30-52 y
16.3	White and Rolf (1948)	PAH	8	males, 20-30 y
16.3	Freeman *et al* (1955)	PAH	15	
16.3	Foa and Foa (1942)	diodrast	6	males, 26-62 y
16.2	Thomasson (1957)	PAH	6	females, 21-40 y
15.9	Bolomey *et al* (1949)	PAH	5	females
15.9	Bucht (1951)	PAH	27	males, 18-44 y
15.7	Lantz *et al* (1981)	video dilution	26	
15.6	Nickel *et al* (1954)	PAH and diodrast	10	females, 24-55 y
15.5	Pfeiffer *et al* (1950)	PAH	11	females, 23-57 y
15.2	Smith *et al* (1952)	PAH	6	adult males
15.2	Wiggins *et al* (1951)	PAH	2	females, 32 and 49 y
15.0	[a]Hogeman (1948)	diodrast	36	males, 20-50 y
14.9	Bucht (1951)	PAH	20	females, 17-45 y
14.8	Wesson (1964)	PAH	4	females, 19-33 y
14.6	[a]Chesley (1939)	diodrast	9	females
14.2	Werko *et al* (1952)	PAH	13	
14.2	Bucht *et al* (1953)	PAH	6	22-30 y
14.0	Ikkos *et al* (1956)	PAH	10	females, 23-52 y
13.3	[a]Hogeman (1948)	diodrast	20	females, 20-50 y
12.5	Svensson *et al* (1982)	Tl	6	males, 33-49 y
12.2	Greene *et al* (1981)	Doppler	16	avg. age 28 y
12.2	Crean *et al* (1986)	microspheres	6	males, 27-67 y

[a]Results reported by Smith (1958).
[b]Results reported by Chapman *et al* (1948).

PCSs in table 4 reflect primarily data for young to middle-aged, normotensive, resting adults who were free of demonstrable renal or cardiac disease. A potential sex dependence in the renal PCO is indicated by the tabulated study values. For example, study values for males were greater than those for females in 17 of the 20 studies in which data could be separated according to sex. The PMCT for all study values in table 4 is 17.5% (17.3-17.7%), for values based only on males is 18.6% (18.4-18.7%), and for values based only on females is 16.6% (16.1-17.0%). We have selected reference PCOs of 19% for the adult male and 17% for the adult female.

3.3. Heart (myocardium)

Estimated PCOs to heart tissue are in the range 3-8% (table 5). The various estimates of central tendency also have a relatively large range (4.1-6.0%), due primarily to variation with measurement technique. Restriction of attention to studies based on the most commonly applied technique, estimation of uptake of nitrous oxide, yields a PMCT of 4.0% (3.8-4.1%). The myocardial PCO in females apparently is 20-30% higher than that in age-matched males (Rowe *et al* 1959, Weinberg *et al* 1964). We have selected 4.0% and 5.0% as the reference myocardial PCOs for adult males and females, respectively.

Table 5. Estimates of the PCO to heart tissue, based on reported measurements on humans with apparently normal myocardial circulation.

% CO	Reference	Method of measurement	Number of subjects	Subject characteristics
8.0	Weinberg *et al* (1964)	I serum albumin	61	females, 20-69 y
6.5	Weinberg *et al* (1964)	I serum albumin	63	males, 20-69 y
6.3	Leight *et al* (1956)	N_2O	8	
6.0	Evans and Iseri (1961)	isotope dilution	9	
4.8	Lavender *et al* (1981)	microspheres	7	
4.7	Goodale and Hackel (1953)	N_2O	3	
4.7	Regan *et al* (1961)	N_2O	9	26-41 y
4.6	Bing *et al* (1950)	N_2O	2	females, 32 and 60 y
4.3	Bargeron *et al* (1957)	N_2O	9	20-56 y
4.3	Crean *et al* (1986)	microspheres	9	8 males, 27-67 y
4.1	Rowe *et al* (1959)	N_2O	15	females
4.0	Yurchak *et al* (1964)	Kr	13	
3.8	[a]Calazel (1954)	N_2O	8	6 males
3.8	Bing (1951)	N_2O	18	
3.4	[a]Kobayashi (1956)	N_2O	15	
3.3	Rowe *et al* (1959)	N_2O	15	males, avg. age 30 y
3.2	[b]Bing (1949)	N_2O		
3.2	Svensson *et al* (1982)	Tl	6	males, avg. age 40 y
3.0	Bing *et al* (1950)	N_2O	4	males, 35-74 y

[a]Results reported by Rowe (1959).
[b]Results reported by Myers (1950).

3.4. Lungs (bronchial circulation)

All blood leaving the right heart passes through the pulmonary circulation. Also, a portion of the systemic circulation called the bronchial circulation supplies nutrients to the lungs. The bronchial PCO has been difficult to quantify, in large part because there is a complex communication system among the pulmonary and bronchial circulations and the heart. The bronchial capillary beds appear to drain mainly into the left atrium and to a lesser extent into the systemic venous system; part of the bronchial venous outflow may arise from blood in the pulmonary circulation; and the bronchial vessels may provide collateral circulation to the pulmonary arterial system in some cases (Aramendia *et al* 1962a,b, Aviado 1965, Cudkowicz 1968, Brobeck 1979). Most estimates of bronchial blood flow in humans are

Table 6. Estimates of the PCO to bronchial tissue based on reported measurements on humans and laboratory animals.

% CO	Reference	Method of measurement	Number of subjects	Subject characteristics
7.6	Evans and Iseri (1961)	isotope dilution	9	humans
5.5	French *et al* (1987)	dye dilution	24	humans
3.0	[a]Aviado (1965)	several methods		dogs
2.5	Behrman and Lees (1971)	microspheres		rhesus monkeys
1.4	Cudkowicz (1968)	dye dilution	28	humans
1.1	[b]Abdel-Fatteh (1966)	dye dilution	5	humans
0.9	[b]Fritts (1961)	dye dilution	9	humans
0.5	Forsyth *et al* (1968)	microspheres		rhesus monkeys

[a]Summary of literature sources.
[b]Results reported by Cudkowicz (1968).

based on the amount of blood returning to the left heart, which provides only a crude estimate of total nutrient flow to lung tissues. Moreover, many of the subjects have been patients under examination for potential heart disease. For these reasons we have supplemented human data with data from relatively detailed studies of bronchial blood flow in laboratory animals.

Estimates of the bronchial PCO in humans, rhesus monkeys, and dogs are in the range 0.5 to 7.6% (table 6). The PMCT for the five fairly crude estimates based on human studies is 3.1% (1.4-3.4%) and for all values including animal studies is 2.2% (1.4-3.3%). The PMCT based on human data agrees with the model proposed by Aviado (1965) for bronchial circulation in the dog but is higher than values obtained in microsphere studies on rhesus monkeys (2.5% and 0.5%). As the reference PCO to bronchial tissue we have selected 2.5% for adult males and females.

Table 7. Estimates of the PCO to segments of the gastrointestinal tract, based on studies on healthy and diseased humans and on laboratory animals.

% CO	Reference	Method of measurement	Number of subjects	Subject characteristics
Stomach and oesophagus				
2.5	Sapirstein (1958)	K		dogs
1.9	Forsyth *et al* (1968)	microspheres		rhesus monkeys
1.7	[a]Guth (1978)	C	5	humans
0.9	[a]Knight (1977)	dye	8	humans
0.9	Tranquilli *et al* (1982)	microspheres		swine
0.3	Ivarsson *et al* (1982)	Kr	20	gall bladder patients
Small intestine				
14.6	Dencker *et al* (1972)	dye dilution	1	female human, 75 y
12.9	Hales (1973)	microspheres		sheep
12.6	Lantz *et al* (1981)	video dilution	15	humans
9.6	Norryd *et al* (1974)	dye dilution	25	humans, avg. age 63 y
9.2	Forsyth *et al* (1968)	microspheres		rhesus monkeys
9.2	Sapirstein (1958)	K		dogs
6.8	Hulten *et al* (1976b, 1977)	Kr	27	human surg. patients
5.9	Tranquilli *et al* (1982)	microspheres		swine
Upper large intestine				
3.7	Dencker *et al* (1972)	dye dilution	1	female human, 75 y
3.0	Sapirstein (1958)	K		dogs
3.0	Forsyth *et al* (1968)	microspheres		rhesus monkeys
2.9	Lantz *et al* (1981)	video dilution	15	humans
2.4	Norryd *et al* (1974)	dye dilution	25	humans, avg. age 63 y
2.1	Hales (1973)	microspheres		sheep
2.0	Tranquilli *et al* (1982)	microspheres		swine
2.0	Hulten *et al* (1976b, 1977)	Kr	25	human surg. patients
1.6	Hulten *et al* (1976a)	venous outflow	6	human patients
Lower large intestine				
2.3	Sapirstein (1958)	K		dogs
2.2	Forsyth *et al* (1968)	microspheres		rhesus monkeys
2.0	Bacaner (1966)			normal female humans
1.9	Lantz *et al* (1981)	video dilution	1	human
1.6	Hales (1973)	microspheres		sheep
1.5	Tranquilli *et al* (1982)	microspheres		swine
1.5	Hulten *et al* (1976b, 1977)	Kr	25	human patients
1.2	Hulten *et al* (1976a)	venous outflow	6	human patients

[a]Results reported by Ivarsson *et al* (1982).

3.5. Gastrointestinal (GI) tract

Data on blood flow to the human GI tract are fragmentary. Selection of a reference PCO to the GI tract was facilitated by supplementing human studies with selected comprehensive studies for laboratory animals and considering separately four segments of the tract: stomach plus oesophagus (S + O), small intestine (SI), upper large intestine (ULI), and lower large intestine (LLI) (table 7). Reported flow rates through the inferior mesenteric artery were assigned to the LLI. Flow through the superior mesenteric artery was divided between the SI and ULI in the ratio 0.8:0.2 based on the masses of these two segments and on human and animal studies in which relative perfusion rates were determined for the two segments (Folkow 1967, Forsyth *et al* 1968, Folkow and Neil 1971, Hales 1973, Hulten *et al* 1976a, b, 1977, Lantz *et al* 1981, Tranquilli *et al* 1982).

Based on combined data for humans and laboratory animals the PMCTs for S + O, SI, ULI, and LLI are 1.2% (0.3-1.4%), 9.6% (9.2-10.1%), 2.4% (2.3-2.5%), and 1.6% (1.5-1.8%), respectively, summing to 14.8% for the entire GI tract. If attention is restricted to human data the PMCTs for S + O, SI, ULI, and LLI are 0.7% (0.3-1.0%), 10.3% (9.2-11.1%), 2.4% (2.3-2.5%), and 1.5% (1.5-1.7%), respectively, summing to 14.9% for the entire GI tract. It is evident from the data that there are particularly large uncertainties associated with estimates of blood flow to the stomach and oesophagus, but any error for those tissues has only a small effect on the estimated flow to the total GI tract. As reference PCOs for S +O, SI, ULI, LLI, and entire GI tract we have selected values of 1.0%, 10%, 2.5%, 1.5%, and 15%, respectively, for the adult male.

The GI tract of the female may represent a larger portion of total body mass than that of the male (ICRP 1975) and hence may receive a greater portion of CO even if the average flow rate per unit mass is independent of sex. Based on results of Norryd *et al* (1974) for 24 male and 13 female subjects, we have assumed that blood flow to the GI tract, expressed in ml min^{-1} per m^2 body surface area, is 1.15 times greater in the female than in the male. This yields a reference PCO of 17% to the GI tract in females. We divide this into reference PCOs of 1.0%, 11%, 3.0%, and 2.0% to the S +O, SI, ULI, and LLI, respectively, in the adult female.

3.6. Spleen

Estimates of blood flow to the human spleen have been based on clearance rates of Xe or Kr; uptake of incompatible red cells, indium-labelled platelets, or microspheres; and video

Table 8. Estimates of the PCO to spleen, based on reported measurements on humans with apparently normal circulation.

% CO	Reference	Method of measurement	Number of subjects	Subject characteristics
6.0	Lavender *et al* (1981)	microspheres	7	heart patients
5.2	Lantz *et al* (1981)	video dilution	12	
4.8	Crean *et al* (1986)	microspheres	6	ages 27-67 y
3.2	Ueda *et al* (1971)	Kr	5	
3.2	Peters *et al* (1980)	In	4	
3.2	Peters *et al* (1984)	In	3	
3.0	[a]Takahashi (1974)	Xe		
3.0	Hughes Jones *et al* (1957)	red cell removal	4	
2.6	Williams *et al* (1968)	Xe	16	various ailments
2.5	Gitlin *et al* (1970)	Xe	9	
2.5	Huchzermeyer *et al* (1977)	Xe	21	

[a]Results reported by Huchzermeyer *et al* (1977).

dilution techniques. Estimated splenic PCOs for adult humans with apparently normal splanchnic circulation (table 8) are in the range 2.5-6.0%, with a PMCT of 3.2% (2.6-3.6%). No information on variation with sex is available. We have selected 3.0% as the reference value for adult males and females.

3.7. Pancreas

The estimated PCOs to pancreas in table 9 are extrapolated from perfusion rates or PCOs determined in large laboratory animals by a variety of methods, most often by uptake or washout of radioactive tracers. The PMCT is 0.9% (0.9-1.0%). We have selected 1.0% as the reference value for pancreatic PCO for male and female adult humans.

Table 9. Estimates of the PCO to the human pancreas, extrapolated from data for monkeys, baboons, dogs, and pigs.

% CO	Reference	Method of measurement	Animal
1.9	Forsyth *et al* (1968)	microspheres	rhesus monkeys
1.6	[a]Fife (1966)		baboons
1.2	Sapirstein (1958)	K	dogs
1.2	[b]Gallavan (1980)	microspheres	dogs
0.9	[c]Burton-Opitz (1912)	stromuhr	dogs
0.9	[b]Frogge (1970)	venous outflow	dogs
0.9	Kaihara *et al* (1968)	microspheres	dogs
0.8	[d]Lundgren (1984)	gas washout	dogs
0.7	Delaney and Grim (1966)	K and Rb	dogs
0.7	[c]Bennett (1933)	stromuhr	dogs
0.7	[b]Semb (1971)	H_2 washout	pigs
0.6	[b]Goodhead (1970)	Rb	dogs

[a]Results reported by Loew (1981).
[b]Results reported by Lundgren (1984).
[c]Results reported by Delaney and Grim (1966).
[d]Reporting results of four studies by other authors.

3.8. Liver

The liver receives blood from the hepatic artery and the portal vein. There is a typically small venous flow collateral to the portal vein that may increase to 10% of CO in cases of portal hypertension (Bosch *et al* 1985). Thus, total blood flow to liver is normally slightly less than the sum of flows through the hepatic artery, pancreas, spleen, and GI tract and may be considerably less in cases of portal hypertension. Separate estimates of PCOs have been made for blood flow through the hepatic artery, the portal vein, and the total liver (table 10).

Most of the reported perfusion rates and PCOs used to derive the estimates for total liver in table 10 were based on the clearance technique. This method depends on the assumptions that the tracer (usually bromsulpthalein (BSP), Rose Bengal, colloidal gold, denatured albumin, indocyanine green, or colloidal chromic phosphate) is extracted from blood exclusively by the liver, and that sampling from a single hepatic vein provides a representative estimate of the total flow (Wade and Bishop 1962, Taplin 1965, Goresky and Groom 1984). The validity of these assumptions depends to a large extent on the tracer. Estimates of hepatic blood flow based on indocyanine green may be among the most reliable (Goresky and Groom 1984), while fairly large underestimates are expected when the tracer is colloidal gold (Taplin 1965).

Table 10. Estimates of the PCO flowing through the hepatic artery, portal vein, or total liver, based on reported measurements on human subjects with normal portal pressure.

% CO	Reference	Method of measurement	Number of subjects	Subject characteristics
Flow through hepatic artery				
8.4	Tygstrup *et al* (1962)	BSP	8	31-73 y
7.0	Chiandussi *et al* (1968)	catheterisation	3	
6.6	Lantz *et al* (1981)	video dilution	14	
5.9	Schenk *et al* (1962)	flow probes	8	avg. age 48 y
5.7	Strandell *et al* (1972)	Xe flow	2	males, 29 y and 50 y
Flow through portal vein				
26.5	Strandell *et al* (1972)	Xe flow	2	males, 29 y and 50 y
24.2	Lantz *et al* (1981)	video dilution	26	
22.7	Moreno *et al* (1967)	flow probe	6	
20.9	Dencker *et al* (1972)	dye dilution	4	males, avg. age 67 y
20.1	Reichle *et al* (1972)	radiopaque drops	6	
18.7	Smith *et al* (1986)	Doppler	85	
18.3	Dencker *et al* (1972)	dye dilution	1	female,age 75 y
17.7	Moriyasu *et al* (1984)	Doppler	88	
16.1	Tygstrup *et al* (1962)	BSP	8	31-73 y
16.0	Chiandussi *et al* (1968)	catheterisation	3	
13.3	Schenk *et al* (1962)	flow meters	8	avg. age 48 y
Total liver				
34.2	Leiberman *et al* (1978)	Kr clearance	5	
32.2	Strandell *et al* (1972)	Xe flow	2	males, 29 and 50 y
31.4	Brandt *et al* (1955)	BSP	10	
30.8	Lantz *et al* (1981)	video dilution	26	
29.1	Wade *et al* (1956)	BSP	5	males, 39-54 y
29.0	[a]Smythe (1961)	denatured albumin	13	
27.9	Price *et al* (1966)	I albumin	11	males
27.9	Winkler and Tygstrup (1960)	indocyanine green/BSP	6	
27.3	Culbertson *et al* (1957)	BSP	8	males 15-44 y
27.2	Reemstma *et al* (1960)	indocyanine green	5	males, 26-56 y
26.7	[a]Baptista (1958)	Au	10	
26.5	Winkler *et al* (1965)	average, 5 methods	8	6 males, 17-59 y
26.0	Shaldon *et al* (1961)	I albumin	14	
25.6	Reynolds *et al* (1953)	BSP	10	males, avg. age 47 y
25.4	Abboud *et al* (1979)	indocyanine green	15	males, 23-29 y
25.0	Feruglio *et al* (1964)	indocyanine green	11	18-60 y
24.5	Tygstrup *et al* (1962)	BSP	8	31-73 y
24.3	Sherlock *et al* (1950)	BSP	31	28 males, 20-68 y
24.1	Mendeloff (1954)	BSP	5	young adult males
24.0	Munnell and Taylor (1947)	BSP	15	females, 21-35 y
24.0	Bradley (1949)	BSP	50	
23.8	Culbertson *et al* (1951)	BSP	8	males
23.8	Caesar *et al* (1961)	indocyanine green	4	2 males, 45-56 y
23.7	Bearn *et al* (1952)	BSP	15	19-61 y
23.7	Bondy *et al* (1949)	urea and BSP	7	
23.4	Levy *et al* (1961)	chromic phosphate	29	
23.3	Bradley *et al* (1952)	BSP	91	73 males
23.3	Dobson *et al* (1953)	chromic phosphate	29	males, 20-26 y
23.0	Chiandussi *et al* (1968)	catheterisation	3	
22.9	Bearn *et al* (1951)	BSP	22	
22.3	Wilkins *et al* (1952)	BSP	21	

22.2	Mueller *et al* (1952)	BSP	1	57 y
21.6	Bosch *et al* (1985)	indocyanine green	11	
21.5	Myers (1950)	BSP	51	
21.4	Kessler *et al* (1954)	BSP	17	males, 22-51 y
20.8	Shackman *et al* (1953)	BSP	18	16 males, 29-70 y
20.6	Myers (1947)	avg., urea and BSP	7	
20.3	Vetter *et al* (1954)	Au	25	18 males
19.6	Keiding (1988)	indocyanine green	6	
19.5	Reichman *et al* (1958)	I serum albumin	14	
19.4	Culbertson *et al* (1951)	BSP	8	males
19.4	Combes (1960)	I Rose Bengal	7	5 males, 24-55 y
19.2	Schenk *et al* (1962)	flow probes	8	avg. age 48 y
18.8	Wiegand *et al* (1960)	indocyanine green	11	males
18.6	Myers *et al* (1950)	BSP	15	
18.3	Epstein *et al* (1961)	BSP	12	21-60 y
17.3	Castenfors *et al* (1960)	BSP	9	avg. age 34 y
17.2	[a]Taplin (1961)	denatured albumin	92	
17.0	Leevy *et al* (1962)	BSP	14	males
16.8	Gilmore and Thompson (1980)	cholic acid	14	avg. age 54 y
16.7	[a]Antognetti (1960)	Au	11	
15.7	[a]Biozzi (1958)	denatured albumin	5	
12.3	[a]Fauvert (1957)	Au	22	
12.3	[a]Taplin (1961)	Au	42	
11.3	[a]Playoust (1959)	Au	20	
11.0	Krook (1956)	Au	13	males, 20-44 y

[a]Results reported by Taplin (1965).

The PMCT of all values for total liver in table 10 is 22.7% (21.4-23.1%) and excluding values based on colloidal gold is 23.3% (22.6-23.4%). The PMCT of seven values based on colloidal gold is 13.8% (12.3-15.8%); six values based on denatured albumin is 20.0% (17.2-22.8%); 25 values based on BSP is 23.0% (22.8-23.3%); eight values based on indocyanine green is 24.0% (23.4-25.0%); and five values based on techniques much different from the tracer extraction method (video dilution, direct catheterisation, flow probes, Kr clearance, Xe flow) is 30.1% (27.9-30.8%).

Another estimate of total blood flow to liver may be obtained by adding separate estimates of arterial and portal flow, although relatively few separate study values are available. The PMCT for all estimates of the PCO flowing through the portal vein is 18.9% (18.4-19.6%), which agrees with the sum of reference PCOs selected for the GI tract, spleen, and pancreas in males. The PMCT of all estimates for the hepatic artery is 6.6% (6.4-6.8%).

As reference PCOs for the hepatic artery and total liver in adult males we have selected the values 6.5%, and 25%, respectively. It is assumed, in effect, that the portal vein carries 18.5% of CO in males (an insignificant digit is retained here for internal consistency) and that 0.5% of the outflow from the GI tract, pancreas, and spleen returns to the heart via collateral circulation.

A few studies based on the clearance method allow separate estimates of liver blood flow in males and females, but the data for females are too sparse to illuminate any subtle differences with sex that may exist. For adult females we have selected the reference values 6.5% and 27% for PCOs flowing through the hepatic artery and total liver, respectively. The additional 2.0% assigned to the total liver (in effect, to the portal vein) of females is consistent with the additional flow assigned to the GI tract of females.

3.9. Adipose tissue

Estimates of the PCO to subcutaneous and other separable adipose tissue in the reference male range from 3.7 to 11.8% (table 11), with the PMCT equal to 5.2% (5.0-6.2%). The blood perfusion rate of adipose tissue may be independent of sex at comparable adiposity, although there could be a slightly lower average perfusion rate in females due to a slight decrease in perfusion with increasing body fat (Larsen *et al* 1966, Larsen and Lassen 1967, Lesser and Deutsch 1967). Assuming a perfusion rate of 28 ml kg^{-1} min^{-1}, independent of sex, we have selected 5.0% as the reference PCO to 12 500 g of subcutaneous and other separable adipose tissue in the reference adult male and 8.5% as the reference value for 17 500 g in the adult female.

Table 11. Estimates of the PCO to adipose tissue in the adult male, based on reported measurements on humans with apparently normal circulation.

% CO	Reference	Method of measurement	Number of subjects	Subject characteristics
11.8	Haggendal *et al* (1967)	Xe, abdomen	15	males, 22-26 y
9.3	Bulow and Madsen (1976)	Xe	8	males, 22-45 y
6.6	Sejrsen (1969)	Xe-133, abdomen	6	males, 22-54 y
6.5	Larsen and Lassen (1967)	Xe, abdomen		adults
6.3	Lundin (1960)	Whole-body N outflow	6	16-45 y
5.2	Larsen *et al* (1966)	Xe	17	males
5.0	Jelnes *et al* (1985)	Xe, feet	10	
4.3	Nielsen *et al* (1968)	Xe	11	avg. age 34 y
4.2	Lesser and Deutsch (1967)	Kr	18	males, 17-75 y
3.8	Sejrsen (1967a)	Kr, leg tissue	9	24-76 y
3.7	Price *et al* (1959)	thiopental model	4	patients

3.10. Skin

The list of estimated PCOs to skin in table 12 represents a considerable distillation of the widely ranging and highly uncertain PCOs to skin (about 0.5-15%) that may be derived from different studies. We have restricted attention to the most commonly applied techniques for quantifying skin blood flow, Xe clearance and plethysmography, with the latter sometimes combined with the NaI clearance technique. Other techniques (heat exchange, oxygen saturation, and clearance of substances other than xenon) have tended to yield highly variable or unreasonably high perfusion rates. However, even estimated PCOs based on the most commonly applied techniques involve considerable uncertainty, not only because of errors associated with the measurement techniques but also because of variability in skin blood flow at different temperatures and in different areas of the body and uncertainties in the total weight of skin in a 73 kg male or 60 kg female. Animal studies were not considered to provide useful supplementary estimates of the PCO to skin.

The plethysmographic method yields an estimate of total blood flow per unit volume in a forearm or lower leg, for example, and subtraction techniques must be applied to obtain estimates of skin or muscle perfusion rates (Cooper *et al* 1955, Wade and Bishop 1962). Indirect estimates obtained in this way may be less accurate for skin than for muscle, which receives most of the blood flow to a limb (Cooper *et al* 1955). Of the numerous plethysmographic studies of blood flow to human limbs, we have selected only a small number whose techniques and assumptions seem particularly well suited to the problem of extracting local skin blood flow.

Flow rates determined for a specific region of the body were adjusted to estimates for total skin by assuming that blood flow in ml kg^{-1} min^{-1} to forearm, thigh, calf, foot, and abdomen skin are 100%, 60%, 70%, 140%, and 80%, respectively, of the average over the entire body. These relative values are based on data of Hertzman and Randall (1948), Bohr (1967), Munck *et al* (1967) and Sejrsen (1969). Flow rates reported for skin of the fingers, toes, and regions of the face and head were not used.

The PMCT of the estimates in table 12 is 5.8% (5.7-5.9%). This would indicate a reference PCO of 6.0% for the adult male and, assuming the same blood flow rate in ml kg^{-1} min^{-1} for both sexes, of 4.5% for the adult female. Because of the particularly large uncertainties associated with our estimated PCOs to skin and the need to achieve mass balance for CO, however, we arbitrarily assigned a reference PCO to skin of 5.0% for both sexes.

Table 12. Selected estimates of the PCO to skin in the adult male, based on reported measurements on healthy humans.

% CO	Reference	Method of measurement	Number of subjects	Subject characteristics
8.6	Zelis *et al* (1969, 1974)	plethys.*, forearm	12	males
7.0	Holloway *et al* (1976)	Xe, forearm	23	20-37 y
6.2	Hertzman and Randall (1948)	plethys., body avg.	2	young males
5.9	Cooper *et al* (1955)	plethys., forearm	31	
5.8	Bohr (1967)	Xe, leg and foot	13	15-60 y
5.7	Kontos *et al* (1966)	plethys., forearm	15	
5.5	Clarke *et al* (1958)	plethys., forearm	4	males, 27-34 y
5.2	Hyman & coworkers (1964-68)	NaI, plethys., arm, calf	23	
4.8	Sejrsen (1967b,1969)	Xe, 4 body parts	18	22-54 y
3.3	Alpert and Coffman (1969)	NaI, plethys., calf	5	

*plethysmography

3.11. Muscle (skeletal)

Estimates of the resting PCO to skeletal muscle vary widely, depending somewhat on the measurement technique (table 13). In the following we compare estimates based on different techniques.

A sensitivity analysis based on reasonable ranges of perfusion rates and fractional masses of adipose tissue, skeleton, skin, and muscle in forearm and leg leads us to conclude that about 50-70% of the resting blood flow to forearm or leg is to skeletal muscle. For conversion of plethysmographic measurements to perfusion rates of muscle we used the midpoint, 60%, which is reasonably consistent with the experimental results of Cooper *et al* (1955), Edholm *et al* (1956), Kontos *et al* (1966), and Zelis *et al* (1969). Under this assumption, the PMCT for 25 plethysmographic studies of forearm blood flow is 15.3% (15.3-16.4%) and for 12 studies of leg blood flow is 14.1% (13.3-14.7%).

The xenon clearance method may provide reasonably accurate estimates of muscle blood flow with proper analysis of multi-exponential clearance (Marcus *et al* 1981), but the commonly applied assumption of a single clearance rate appears to lead to substantial underestimates (Bolme and Edwall 1971, Cerretelli *et al* 1984, Ozolin 1986). The PMCT of the 11 xenon-based estimates is 10.4% (9.6-10.8%). Data of Cerretelli *et al* (1984) and Marcus *et al* (1981) indicate that the xenon clearance technique as commonly applied may underestimate the actual perfusion rate by a factor of roughly 1.7. Upward adjustment of the xenon-based estimates by this factor would raise the PMCT to 17.7% (16.3-18.4%).

Six studies based on other techniques (dye dilution or clearance rates for various tracers) yield a PMCT of 19.1% (14.6-19.8%). Reported values based on certain strain gauge techniques were excluded because they appeared to yield systematically low estimates.

As the reference PCO to skeletal muscle in the adult male we have chosen 17%, which is the (rounded) mean of the estimates obtained by the different methods (the adjusted xenon estimate was used). The assumption that the blood perfusion rate of skeletal muscle (in ml kg^{-1} min^{-1}) is independent of sex would yield a reference PCO to skeletal muscle of 12% for the adult female.

Table 13. Estimates of the PCO to skeletal muscle in the adult male, based on measurements on healthy human subjects.

% CO	Reference	Method of measurement	Number of subjects	Subject characteristics
42.2	Vroman *et al* (1983)	plethys.*, forearm	10	males, 19-27 y
27.1	Holzman *et al* (1964)	dye, forearm	6	adult males
24.9	Zelis *et al* (1969)	plethys., forearm	12	
22.6	Lundin (1960)	whole-body N outflow	6	16-45 y
21.8	Rusch *et al* (1981)	plethys., calf	6-9	8 studies
20.9	Mellander and Oberg (1967)	plethys., forearm	12	young males
19.4	Slaughter *et al* (1948)	plethys., forearm	7	20-30 y
19.2	Johnson and Rowell (1975)	antipyrine, forearm	5	males, 20-30 y
19.0	Andres *et al* (1954)	dye, forearm	7	
18.2	Edholm *et al* (1956)	plethys., forearm	12	males
18.2	Vanderhoof *et al* (1961)	plethys., forearm	15	male students
17.8	Roberts *et al* (1977)	plethys., forearm	5	22-32 y
17.6	Rusch *et al* (1981)	plethys., forearm	6-9	11 studies
16.7	Dahn (1965)	plethys., calf	26	males, >45 y
16.3	Shepherd and Warren (1960)	N_2O, calf	3	males
16.3	Greenfield and Patterson (1954)	plethys., forearm	4	young males
16.1	Abboud *et al* (1979)	plethys., forearm	15	males
15.6	Strandell and Wahren (1963)	plethys., calf	13	avg. age 59 y
15.6	Strandell and Shepherd (1962)	Xe, forearm	6	males
15.6	Barcroft and Edholm (1946)	plethys., forearm	7	males, 20-40 y
15.5	Eklund *et al* (1974)	plethys., forearm	14	young males
15.3	Cooper *et al* (1955)	plethys., forearm	31	adults
15.2	Alpert and Coffman (1969)	plethys., calf	7	
15.1	Lindbjerg (1966)	plethys., calf		
14.7	Mottram and Brown (1963)	plethys., forearm	5	young males
14.7	Hillestad (1963)	plethys., calf	48	
14.7	Grimby *et al* (1967)	Xe, calf	15	males, 21-32 y
14.6	Amery *et al* (1969)	Xe, tibial muscle	24	males, 17-75 y
14.6	Baltzan *et al* (1962)	dye	49	males
14.0	Williams *et al* (1978)	plethys., forearm	11	
13.9	Bevegard and Oro (1969)	plethys., forearm	9	males
13.6	Corcondilas *et al* (1964)	plethys., forearm	4	
13.5	Halliday (1960)	plethys., forearm	3	male med. students
13.4	London *et al* (1985)	plethys., forearm	4	normotensives
13.2	Barcroft *et al* (1963)	plethys., forearm	25	adults
13.0	Mottram (1955)	plethys., forearm	16	
12.8	Lassen (1964)	Xe and Na, leg	10	
12.6	Zelis *et al* (1974)	plethys., forearm	22	
11.9	Siggaard-Andersen and Bonde Petersen (1967)	plethys., calf	10	19-22 y
11.9	Slaughter *et al* (1948)	plethys., leg	7	20-30 y
11.7	Patterson and Shepherd (1954)	plethys., forearm	12	males, 18-30 y

11.4	Beaconsfield and Ginsburg (1955)	plethys., calf	3	
11.1	Halliday (1960)	plethys., calf	3	male med. students
10.8	Dahn (1965)	plethys., calf	26	males, <45 y
10.2	Kontos *et al* (1966)	plethys., forearm	15	
9.9	Lindbjerg (1966)	Xe, anterior tibia	23	18-51 y
9.8	Siggaard-Andersen and Bonde Petersen (1967)	Xe, calf	10	19-22 y
9.6	Lassen *et al* (1964)	Xe, leg	44	male adults
9.5	Tonnesen (1964)	Xe, gastrocnemius	4	young subjects
9.3	Nilsson and Ingvar (1967)	Xe, tibial muscle	9	19-46 y
9.0	Beaconsfield and Ginsburg (1955)	plethys., forearm	3	
8.3	Allwood (1958)	plethys., calf	10	males, 18-24 y
7.2	Christensen (1968)	Xe, tibial muscle	41	adults
5.7	Alpert and Coffman (1969)	Xe, calf	7	avg. age 27 y

*plethysmography

3.12. Skeleton

Reported PCOs to the skeleton of man and laboratory animals range from less than 1.0% to more than 25% (see the compilations by Brookes 1974, Shoshenko 1975, Van Dyke *et al* 1975). The smaller range indicated in table 14 resulted from including only (1) recalculated PCOs based on human subjects and (2) estimates for laboratory animals based on the microsphere uptake method, which may be the most accurate technique for measuring skeletal blood flow (Tothill 1984).

Table 14. Selected estimates of the PCO to skeleton, based on human studies and selected studies on laboratory animals.

% CO	Reference	Method of measurement	Number of subjects	Subject characteristics
12.9	Lahtinen *et al* (1981-82)	Xe, proximal femur	72	adult humans
9.6	Kelly (1983)	microspheres, bone flow		mature dogs
6.7	Tothill (1984)	microspheres, total skel.		dogs
4.8	Tothill (1984)	microspheres, total skel.		rabbits
4.7	Shim *et al* (1971)	Sr, leg	1	human, 26 y
4.5	Tothill (1984)	microspheres, total skel.		rats
4.0	Wootton *et al* (1976)	F, total skeleton	8	male humans
3.3	Van Dyke *et al* (1971)	F, total skeleton	4	humans
2.5	[a]Shoskenko (1975)			humans

[a]Average of three studies by others.

The PMCT of all values in table 14 is 5.9%, but the range of measures of central tendency is large (4.4-12.9%) because of a heavily weighted value (12.9%) based on a small portion of the human skeleton. Elimination of this value would yield a PMCT of 4.2% (4.0-5.0%). We have selected 5.0% as the reference PCO to skeleton of adult males and females.

3.13. Thyroid

Estimates of blood flow to the thyroids of humans and laboratory animals are summarised in table 15. Values for human subjects are based on unproven assumptions concerning iodine clearance by the thyroid and may not be any more reliable for our purpose than

values extrapolated from more direct observations on laboratory animals. The PMCT of the tabulated values is 1.6% (1.4-1.9%). We have selected 1.5% as the reference PCO to the thyroid gland in both sexes.

Table 15. Typical estimates of PCOs to thyroid, based on reported measurements on man and laboratory animals.

% CO	Reference	Method of measurement	Number of subjects	Subject characteristics
2.2	Pochin (1950)	I	12	normal humans
1.9	Myant *et al* (1949)	I	11	control humans
1.5	[a]Soderberg (1959)			
1.4	Hales (1973)	microspheres		sheep
1.0	[b]Guyton (1982)			
0.2	[c]Fife (1966)			baboons

[a]Summary of 13 studies of man and laboratory animals.
[b]Value attributed to Sapirstein.
[c]Results reported by Loew (1981).

3.14. Other

Organs and tissues considered to this point constitute about 85% of total body weight and have been assigned 96.5% of CO in males and 96% of CO in females. The remainder, including adrenals, lymph nodes, salivary glands, tongue, sex glands, eyes, spinal cord, urinary bladder, pituitary, and all other organs, tissues, and fluids not considered in previous sections, is referred to as 'other'. About two-thirds of other is made up of blood, GI tract contents, urine, and other material that may be excluded from our analysis. Estimates of blood flow to the most highly perfused tissues in the remaining one-third of other, based on selected studies on large laboratory animals, are given in table 16. Noteworthy among these estimates are the high flow rate indicated for the adrenal glands (a PMCT of 0.3% of CO to tissue constituting 0.02% of the weight of the human body) and the large total blood flow to lymph nodes (about 1.7% of CO) indicated by measurements on rhesus monkeys and sheep.

The sum of PMCTs (or medians or means) for the listed organs is about 3.0% of CO. Remaining tissues not considered in table 16 (for example, separable connective tissues) may constitute about 4% of total body mass but are expected to be poorly perfused. If we assumed, for example, that the perfusion rate is the same as for adipose tissue (the most poorly perfused tissue considered to this point), we would estimate that these tissues receive roughly 1% of CO. Thus, as a crude estimate, we would expect other to receive about 4% of CO. This is in reasonable agreement with the portions of CO not already assigned. Thus, the PCOs to other needed to achieve mass balance (3.5% in males and 4.0% in females) appear to be reasonable choices as reference PCOs to other. Clearly, this indicated difference with sex should not be regarded as significant.

4. Summary

In this review we have attempted to derive a reliable description of the distribution of resting blood flow in typical human adult males and females. Future work will be directed toward improved characterisation of blood flow for different age groups and different levels of activity.

Table 16. Estimates of PCOs to remaining organs and tissues, based on selected studies on laboratory animals.

% CO	Reference	Method of measurement	Animal
Adrenal glands			
1.1	Hartman *et al* (1955)	venous outflow	dogs
0.5	Fixler *et al* (1976)	microspheres	dogs
0.3	Behrman and Lees (1971)	microspheres	rhesus monkeys
0.2	Hales (1973)	microspheres	sheep
0.2	[a]Fife (1966)		baboons
0.1	Forsyth *et al* (1968)	microspheres	rhesus monkeys
Lymph nodes			
1.7	Forsyth *et al* (1968)	microspheres	rhesus monkeys
1.6	Hales (1973)	microspheres	sheep
Salivary glands			
0.5	Eliassen *et al* (1973)		cat, dog, and piglet
0.3	[b]Terroux *et al* (1959)		dogs
Tongue			
0.7	Sapirstein (1958)	K	dogs
0.3	Hales (1973)	microspheres	sheep
0.3	Fixler *et al* (1976)	microspheres	dogs
Testes			
0.1	Wax and Petersen (1967)	Xe	dogs
0.1	Forsyth *et al* (1968)	microspheres	rhesus monkeys
Prostate			
0.1	[c]Andersson (1967)		dogs
Eyes			
0.1	Forsyth *et al* (1968)	microspheres	rhesus monkeys
Spinal cord			
0.08	[c]Smith (1969)		goats
Urinary bladder			
0.06	Forsyth *et al* (1968)	microspheres	rhesus monkeys
Pituitary			
0.006	Hales (1973)	microspheres	sheep

[a]Results reported by Loew (1981).
[b]Includes studies by others.
[c]Results reported by Cowles *et al* (1971).

Recommended values for PCOs in reference adult males and females are summarised in table 17. Also given in table 17 are best estimates of blood perfusion rates of organs and tissues in ml kg^{-1} min^{-1}. These perfusion rates have been based on PMCTs given in the text and, in some cases, on original data, rather than strictly on reference PCOs, COs, and organ masses. To avoid an appearance of great precision, we rounded perfusion rates to an extent depending on the quantity and quality of the data, and we assigned values estimated for males to both sexes where no significant difference with sex was indicated.

In applications of these reference PCOs it should be kept in mind that the values given for males may be more reliable overall than those for females because they are based on a

larger data set. Still, the sex-dependent distributions indicated in table 17 serve to point out to modellers some potentially important qualitative differences with sex that may affect the accuracy of biokinetic models. Differences in PPCOs to skeletal muscle and adipose tissue arise because of the large differences with sex in the percentage of total body mass represented by each tissue. The lower PCO to the female kidney is consistent with the fact

Table 17. Proposed reference values for resting blood flow to organs and tissues of typical 35 y old male and female.

	Percentage of cardiac output		Blood perfusion rate (ml kg^{-1} min^{-1})	
Organ or tissue	Male	Female	Male	Female
Adipose tissue	5	8.5	28	28
Brain	12	12	560	560
Gastrointestinal tract	15	17	–	–
Stomach and oesophagus	(1)*	(1)	400	400
Small intestine	(10)	(11)	1000	1000
Upper large intestine	(2.5)	(3)	800	800
Lower large intestine	(1.5)	(2)	700	700
Heart	4	5	800	1000
Kidneys	19	17	4000	3500
Liver (total)	(25)	(27)	1000	1100
Arterial	6.5	6.5	250	250
Portal	(18.5)	(20.5)	750	850
Lungs	2.5	2.5	400	400
Muscle (skeletal)	17	12	38	38
Pancreas	1	1	600	600
Skeleton	5	5	30	30
Skin	5	5	120	120
Spleen	3	3	1200	1200
Thyroid	1.5	1.5	5000	5000
Other	3.5	4	–	–
Lymph nodes	(1.7)	(1.7)	500	500
Adrenal glands	(0.3)	(0.3)	2000	2000
Balance	(1.5)	(2)		
Total	100.0	100.0		

*Values in parentheses are also represented elsewhere in the list.

that the glomerular filtration rate is roughly 10% less per unit body surface in females (Cunningham 1982). The lower PCOs to skeletal muscle and kidneys in females do not appear to be fully compensated for by the higher PCO to adipose tissue and hence PCOs to some other organs must be higher in females. Some evidence indicates that PCOs to the myocardium and gastrointestinal tracts may be higher in females. For most organs, however, there is still too little information for females to distinguish subtle differences with sex in blood flow rates or PCOs.

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References

Aas K and Blegen E 1949 The renal blood flow and the glomerular filtration rate in congestive heart failure and some other clinical conditions *Scand. J. Clin. Lab. Invest.* **1** 22-32

Abboud F M, Eckberg D L, Johannsen J U and Mark A L 1979 Carotid and cardiopulmonary baroreceptor control of splanchnic and forearm vascular resistance during venous pooling in man *J. Physiol.* **286** 173-84

Alexander S C, Smith T C, Strobel G, Stephen G W and Wollman H 1968 Cerebral carbohydrate metabolism of man during respiratory and metabolic alkalosis *J. Appl. Physiol.* **24** 66-72

Allwood M J 1958 Blood flow in the foot and calf in the elderly; a comparison with that in young adults *Clin. Sci.* **17** 331-8

Alpert J S and Coffman J D 1969 Effect of intravenous epinephrine on skeletal muscle, skin, and subcutaneous blood flow *Am. J. Physiol.* **216** 156-60

Altman P L and Dittmer D S 1972 *Biology Data Book* Vol I (Bethesda: Federation of American Societies for Experimental Biology)

Amery A, Bossaert H and Verstraete M 1969 Muscle blood flow in normal and hypertensive subjects *Am. Heart J.* **78** 211-6

Andres R, Zierler K L, Anderson H M, Stainsby W N, Cader G, Ghrayyib A S and Lilienthal J L Jr 1954 Measurement of blood flow and volume in the forearm of man; with notes on the theory of indicator-dilution and on production of turbulence, hemolysis, and vasodilation by intra-vascular injection *J. Clin. Invest.* **33** 482-504

Aramendia P, de Letona J and Aviado D M 1962a Responses of the bronchial veins in a heart-lung bronchial preparation *Circ. Res.* **10** 3-10

— 1962b Exchange of blood between pulmonary and systemic circulations via bronchopulmonary anastomoses *Circ. Res.* **11** 870-9

Aurell M, Fritjofsson A and Grimby G 1966 Renal extraction of para-aminohippurate during variations in renal blood flow and tubular load in man *Clin. Sci.* **31** 461-71

Avasthi P S, Greene E R and Voyles W F 1987 Noninvasive Doppler assessment of human postprandial renal blood flow and cardiac output *Am. J. Physiol.* **252** F1167-74

Aviado D M 1965 *The Lung Circulation,* vol I, *Physiology and Pharmacology* (New York: Pergamon Press)

Bacaner M B 1966 Quantitative measurement of regional colon blood flow in the normal and pathological human bowel *Gastroenterology* **51** 764-77

Baltzan M A, Andres R, Cader G and Zierbler K L 1962 Heterogeneity of forearm metabolism with special reference to free fatty acids *J. Clin. Invest.* **41** 116-25

Barclay J A, Cooke W T and Kenney R A 1947a Observations on the effects of adrenalin on renal function and circulation in man *Am. J. Physiol.* **151** 621-5

Barclay J A, Cooke W T, Kenney R A and Nutt M E 1947b The effects of water diuresis and exercise on the volume and composition of the urine *Am. J. Physiol.* **148** 327-37

Barcroft H and Edholm O G 1946 Temperature and blood flow in the human forearm *J. Physiol.* **104** 366-76

Barcroft H, Greenwood B and Whelan R F 1963 Blood flow and venous oxygen saturation during sustained contraction of the forearm muscles *J. Physiol.* **168** 848-56

Bargeron L M Jr, Ehmke D, Gonlubol F, Castellanos A, Siegel A and Bing R J 1957 Effect of cigarette smoking on coronary blood flow and myocardial metabolism *Circulation* **15** 251-7

Beaconsfield P and Ginsburg J 1955 Effect of changes in limb posture on peripheral blood flow *Circ. Res.* **3** 478-82

Bearn A G, Billing B H and Sherlock S 1951 The effect of adrenaline and noradrenaline on hepatic blood flow and splanchnic carbohydrate metabolism in man *J. Physiol.* **115** 430-41

— 1952 The response of the liver to insulin in normal subjects and in diabetes mellitus: Hepatic vein catheterisation studies *Science* **11** 151-65

Behrman R E and Lees M H 1971 Organ blood flows of the fetal, newborn and adult rhesus monkey *Biol. Neonate* **18** 330-40

Bell G H, Davidson J N and Scarborough H 1968 *Textbook of Physiology and Biochemistry* (London: Livingstone)

Bernsmeier A and Siemons K 1953 Die Messung der Hirndurchblutung mit der Stickoxydulmethode *Pflugers Arch.* **258** 149-62

Bernstein E F (ed) 1985 *Noninvasive Diagnostic Techniques in Vascular Disease* (St. Louis, MO: C V Mosby)

Bevegard S and Oro L 1969 Effect of prostaglandin E_1 on forearm blood flow *Scand. J. Clin. Lab. Invest.* **23** 347-53

Bing R J 1951 The coronary circulation in health and disease as studied by coronary sinus catheterization *Bull. NY Acad. Med.* **27** 407-24

Bing R J, Maraist F M, Dammann J F, Draper A, Heimbecker R, Daley R, Gerard R and Calazel P 1950 Effect of strophanthus on coronary blood flow and cardiac oxygen consumption of normal and failing human hearts *Circulation* **2** 513-6

Bohr H 1967 Measurement of the blood flow in the skin with radioactive xenon *Scand. J. Clin. Lab. Invest.* Suppl. **99** 60-1

Bolme P and Edwall L 1971 Dissociation of tracer disappearance rate and blood flow in isolated skeletal muscle during various vascular reactions *Acta Physiol. Scand.* **82** 17-27

Bolomey A A, Michie A J, Michie C, Breed E S, Schreiner G E and Lauson H D 1949 Simultaneous measurement of effective renal blood flow and cardiac output in resting normal subjects and patients with essential hypertension *J. Clin. Invest.* **28** 10-7

Bondy P K, James D F, and Farrar B W 1949 Studies of the role of the liver in human carbohydrate metabolism by the venous catheter technic. I. Normal subjects under fasting conditions and following the injection of glucose *J. Clin. Invest.* **28** 238-44

Borisov B K and Marei A N 1974 Weight parameters of adult human skeleton *Health Phys.* **27** 224-9

Bosch J, Mastai R, Kravetz D, Bruix J, Rigau J and Rodes J 1985 Measurement of azygos venous blood flow in the evaluation of portal hypertension in patients with cirrhosis *J. Hepatol.* **1** 125-39

Bradley S E 1949 Variations in hepatic blood flow in man during health and disease *New Eng. J. Med.* **240** 456-69

Bradley S E and Halperin M H 1947 Renal oxygen consumption and sodium *p*-aminohippurate (PAH) extraction in normal man during abdominal compression *Fed. Proc.* **6** 80

Bradley S E, Ingelfinger F J and Bradley G P 1952 Hepatic circulation in cirrhosis of the liver *Circulation* **5** 419-29

Brandt J L, Castleman L, Ruskin H D, Greenwald J, Kelly J J and Jones A 1955 The effect of oral protein and glucose feeding on splanchnic blood flow and oxygen utilization in normal and cirrhotic subjects *J. Clin. Invest.* **34** 1017-25

Brobeck J R 1979 *Best and Taylor's Physiological Basis of Medical Practice* (Baltimore: Williams and Wilkins)

Brookes M 1974 Approaches to non-invasive blood flow measurement in bone *Biomed. Eng.* **9** 342-7

Brun C, Hilden T and Raaschou F 1947a The maximum tubular excretion of diodrast in the normal human kidney *Acta Med. Scand.* **127** 464-70

— 1947b On the excretion of *p*-aminohippuric acid through the kidneys *Acta Med. Scand.* **127** 471-9

Bucht H 1949 Examination of the renal plasma flow by means of para-amino-hippuric acid (PAH) using one intramuscular injection *Scand. J. Clin. Lab. Invest.* **1** 126-30

— 1951 Studies on renal function in man with special reference to glomerular filtration and renal plasma flow in pregnancy *Scand. J. Clin. Lab. Invest.* Suppl. **3** 1-64

Bucht H, Ek J, Eliasch H, Holmgren A, Josephson B and Werko L 1953 The effect of exercise in the recumbent position on the renal circulation and sodium excretion in normal individuals *Acta Physiol. Scand.* **28** 95-100

Bulow J and Madsen J 1976 Adipose tissue blood flow during prolonged, heavy exercise *Pflugers Arch.* **363** 231-4

Caesar J, Shaldon S, Chiandussi L, Guevara L and Sherlock S 1961 The use of indocyanine green in the measurement of hepatic blood flow and as a test of hepatic function *Clin. Sci.* **21** 43-57

Cargill W H 1949 The measurement of glomerular and tubular plasma flow in the normal and diseased human kidney *J. Clin. Invest.* **28** 533-8

Castenfors H, Eliasch H and Hultman E 1960 The splanchnic blood flow and oxygen consumption estimated in man by the bromsulphalein method with special reference to the influence of the peripheral dye level *Scand. J. Clin. Invest.* **12** 158-71

Cerretelli P, Marconi C, Pendergast D, Meyer M, Heisler N and Piiper J 1984 Blood flow in exercising muscles by xenon clearance and by microsphere trapping *J. Appl. Physiol.* **56** 24-30

Chapman C B, Henschel A, Minckler J, Forsgren A and Keys A 1948 The effect of exercise on renal plasma flow in normal male subjects *J. Clin. Invest.* **27** 639-44

Chasis H, Redish J, Goldring W, Ranges H A and Smith H W 1945 The use of sodium *p*-aminohippurate for the functional evaluation of the human kidney *J. Clin. Invest.* **24** 583-8

Chiandussi L, Greco F, Sardi G, Vaccarino A, Ferraris C M and Curti B 1968 Estimation of hepatic arterial and portal venous blood flow by direct catheterization of the vena porta through the umbilical cord in man: Preliminary results *Acta Hepato-splenol.* **15** 166-71

Christensen N J 1968 The significance of work load and injected volume in xenon-133 measurement of muscular blood flow *Acta Med. Scand.* **183** 445-7

Clarke R S J, Hellon R F and Lind A R 1958 Vascular reactions of the human forearm to cold *Clin. Sci.* **17** 165-79

Combes B 1960 Estimation of hepatic blood flow in man and in dogs by I-131- labeled rose bengal *J. Lab. Clin. Med.* **56** 537-43

Cooper K E, Edholm O G and Mottram R F 1955 The blood flow in skin and muscle of the human forearm *J. Physiol.* **128** 258-67

Corcondilas A, Koroxenidis G T and Shepherd J T 1964 Effect of a brief contraction of forearm muscles on forearm blood flow *J. Appl. Physiol.* **19** 142-6

Cowles A L, Borgstedt H H and Gillies A J 1971 Tissue weights and rates of blood flow in man for the prediction of anesthetic uptake and distribution *Anesthesiology* **35** 523-6

Crean P A, Pratt T, Davies G J, Myers M, Lavender P and Maseri A 1986 The fractional distribution of the cardiac output in man using microspheres labelled with technetium-99m *Br. J. Radiol.* **59** 209-15

Crosley A P Jr, Brown J F, Huston J H, Emanuel D A, Tuchman H, Castillo C and Rowe G G 1956 The adaptation of the nitrous oxide method to the determination of renal blood flow and *in vivo* renal weight in man *J. Clin. Invest.* **35** 1340-4

Crumpton C W and Murphy Q R 1952 Effects of hexamethonium bromide upon hemodynamics of cerebral and coronary circulation in hypertension *J. Clin. Invest.* **31** 622

Cudkowicz L 1968 *The Human Bronchial Circulation in Health and Disease* (Baltimore: Williams and Wilkins)

Culbertson J W, Eckstein J W, Kirkendall W M and Bedell G N 1957 General hemodynamics and splanchnic circulation in patients with coarctation of the aorta *J. Clin. Invest.* **36** 1537-45

Culbertson J W, Wilkins R W, Ingelfinger F J and Bradley S E 1951 The effect of the upright posture upon hepatic blood flow in normotensive and hypertensive subjects *J. Clin. Invest.* **30** 305-11

Cunningham J J 1982 Body composition and resting metabolic rate: the myth of feminine metabolism *Am. J. Clin. Nutr.* **36** 721-6

Dahn I 1965 On clinical use of venous occlusion plethysmography of calf: I. Methods and controls *Acta Chir. Scand.* **130** 42-60

Davies D F and Shock N W 1950 Age changes in glomerular filtration rate, effective renal plasma flow, and tubular excretory capacity in adult males *J. Clin. Invest.* **29** 496-507

Delaney J P and Grim E 1966 Influence of hormones and drugs on canine pancreatic blood flow *Am. J. Physiol.* **211** 1398-402

Dencker H, Gothlin J, Olin T and Tibblin S 1972 Portal circulation in humans studied by a dye-dilution technique *Eur. Surg. Res.* **4** 81-9

Dewar H A and Davidson L A G 1958 The cerebral blood flow in mitral stenosis and its response to carbon dioxide *Br. Heart J.* **20** 516-22

De Wardener H E and McSwiney R R 1951 Renal hemodynamics in vaso-vagal fainting due to hemorrhage *Clin. Sci.* **10** 209-17

Dobson E L, Warner G F, Finney C R and Johnston M E 1953 The measurement of liver circulation by means of the colloid disappearance rate: I. Liver blood flow in normal young men *Circulation* **7** 690-5

Edelman I S, Zweifach B W, Escher D J W, Grossman J, Mokotoff R, Weston R E, Leiter L and Shorr E 1950 Studies on VEM and VDM in blood in relation to renal hemodynamics and renal oxygen extraction in chronic congestive heart failure *J. Clin. Invest.* **29** 925-34

Edholm O G, Fox R H and MacPherson R K 1956 The effect of body heating on the circulation in skin and muscle *J. Physiol.* **134** 612-9

Eklund B, Kaijser L and Knutsson E 1974 Blood flow in resting (contralateral) arm and leg during isometric contraction *J. Physiol.* **240** 111-24

Eliassen E, Folkow B and Hilton S 1973 Blood flow and capillary filtration capacities in salivary and pancreatic glands as compared with skeletal muscle *Acta Physiol. Scand.* **87** 11A-12A

Epstein R M, Wheeler H O, Frumin M J, Habif D V, Papper E M and Bradley S E 1961 The effect of hypercapnia on estimated hepatic blood flow, circulating splanchnic blood volume, and hepatic sulfobromophthalein clearance during general anesthesia in man *J. Clin. Invest.* **40** 592-8

Evans J R and Iseri L T 1961 Estimation of coronary and bronchial blood flow by isotope-dilution technic *Circulation* **24** 929

Fazekas J F, Alman R W and Bessman A N 1952 Cerebral physiology of the aged *Am. J. Med. Sci.* **223** 245-57

Feruglio F S, Greco F, Cesano L, Indovina D, Sardi G and Chiandussi L 1964 Effect of drug infusion on the systemic and splanchnic circulation: I. Bradykinin infusion in normal subjects *Clin. Sci.* **26** 487-91

Fishman A P, Maxwell M H, Crowder C H and Morales P 1951 Kidney function in cor pulmonale. Particular consideration of changes in renal hemodynamics and sodium excretion during variation in level of oxygenation *Circulation* **3** 703-21

Fixler D E, Atkins J M, Mitchell J H and Horwitz L D 1976 Blood flow to respiratory, cardiac, and limb muscles in dogs during graded exercise *Am. J. Physiol.* **231** 1515-9

Foa P P and Foa N L 1942 A simple method for determining effective renal blood flow and tubular excretory mass in man *Proc. Soc. Exp. Biol. Med.* **51** 375-8

Folkow B 1967 Regional adjustments of intestinal blood flow *Gastroenterology* **52** 423-4

Folkow B and Neil E 1971 *Circulation* (New York: Oxford University Press)

Forsyth R P, Nies A S, Wyler F, Neutze J and Melmon K L 1968 Normal distribution of cardiac output in the unanesthetized, restrained rhesus monkey *J. Appl. Physiol.* **25** 736-41

Freeman O W, Mitchell G W, Wilson J S, Fitzhugh F W, Merrill A J, Burns B and Cavin E 1955 Renal hemodynamics, sodium and water excretion in supine exercising normal and cardiac patients *J. Clin. Invest.* **34** 1109-13

French W J, Haskell R J, Knouse R W and Criley J M 1987 Left ventricular derived cardiac output *Am. J. Cardiol.* **59** 142-4

Friedman M, Selzer A and Rosenblum H 1941 The renal blood flow in coarctation of the aorta *J. Clin. Invest.* **20** 107-11

Ganong W F 1979 *Review of Medical Physiology* (Los Altos, CA: Lange Medical)

Gilmore I T and Thompson R P H 1980 Plasma clearance of oral and intravenous cholic acid in subjects with and without chronic liver disease *Gut* **21** 123-7

Gitlin N, Grahame G R, Kreel L, Williams H S and Sherlock S 1970 Splenic blood flow and resistance in patients with cirrhosis before and after portacaval anastomoses *Gastroenterology* **59** 208-13

Goldring W, Chasis H, Ranges H A and Smith H W 1940 Relations of effective renal blood flow and glomerular filtration to tubular excretory mass in normal man *J. Clin. Invest.* **19** 739-50

Goodale W T and Hackel D B 1953 Measurement of coronary blood flow in dogs and man from rate of myocardial nitrous oxide desaturation *Circ. Res.* **1** 502-8

Gordon G S 1956 Influence of steroids on cerebral metabolism in man *Recent Prog. Horm. Res.* **12** 153-70

Goresky C A and Groom A C 1984 *Handbook of Physiology* vol 4 *The Cardiovascular System* eds E M Renkin and C C Michel (Bethesda MD: American Physiological Society) pp 689-780

Granger G N and Bulkley G B eds 1981 *Measurement of Blood Flow. Applications to the Splanchnic Circulation* (Baltimore, MD: Williams and Wilkins)

Greene E R, Venters M D, Avasthi P S, Conn R L and Jahnke R W 1981 Noninvasive characterization of renal artery blood flow *Kidney Int.* **20** 523-9

Greenfield A D M and Patterson G C 1954 The effect of small degrees of venous distension on the apparent rate of blood inflow to the forearm *J. Physiol.* **125** 525-33

Grimby G J 1965 Renal clearances during prolonged supine exercise at different loads *J. Appl. Physiol.* **20** 1294-8

Grimby G, Haggendal E and Saltin B 1967 Local xenon-133 clearance from the quadriceps muscle during exercise in man *J. Appl. Physiol.* **22** 305-10

Guyton A C 1982 *Human Physiology and Mechanisms of Disease* (Philadelphia: Saunders)

Haggendal E, Steen B and Svanborg A 1967 Measurement of blood flow through human abdominal subcutaneous fat tissue by local injection of radioactive xenon *Acta Med. Scand.* **181** 215-7

Hales J R S 1973 Radioactive microsphere measurement of cardiac output and regional tissue blood flow in the sheep *Pflugers Arch.* **344** 119-32

Halliday J A 1960 Blood flow in the human calf after prolonged walking *Am. Heart J.* **60** 110-5

Harris P and Heath D 1977 *The Human Pulmonary Circulation* (New York: Churchill Livingstone)

Hartman F A, Brownell K A and Liu T Y 1955 Blood flow through the dog adrenal *Am. J. Physiol.* **180** 375-7

Heller B I and Jacobson W E 1950 Renal hemodynamics in heart disease *Am. Heart. J.* **39** 188-204

Hertzman A B and Randall W C 1948 Regional differences in the basal and maximal rates of blood flow in skin *J. Appl. Physiol.* **1** 234-41

Heyman A, Patterson J L Jr and Duke T W 1952 Cerebral circulation and metabolism in sickle cell and other chronic anemias, with observations on the effects of oxygen inhalation *J. Clin. Invest.* **31** 824-8

Heyman A, Patterson J L Jr, Duke T W and Battey L L 1953 The cerebral circulation and metabolism in arteriosclerotic and hypertensive cerebrovascular disease *New Eng. J. Med.* **249** 223-9

Hillestad L K 1963 The peripheral blood flow in intermittent claudication: V. Plethysmographic studies. The significance of the calf blood flow at rest and in response to timed arrest of the circulation *Acta Med. Scand.* **174** 23-41

Hollenberg N K, Epstein M, Basch R I, Merrill J P and Hickler R B 1969 Renin secretion in the patient with hypertension: Relationship to intrarenal blood flow distribution *Circ. Res.* **24** I113-22

Holloway G A, Daly C H, Kennedy D and Chimoskey J J 1976 Effects of external pressure loading on human skin blood flow measured by Xe-133 clearance *J. Appl. Physiol.* **40** 597-600

Huchzermeyer H, Schmitz-Feuerhake I and Reblin T 1977 Determination of splenic blood flow by inhalation of radioactive rare gases *Eur. J. Clin. Invest.* **7** 345-9

Hughes Jones N C, Mollison P L and Veall N 1957 Removal of incompatible red cells by the spleen *Br. J. Haematol* **3** 125-33

Hulten L, Jodal M, Lindhagen J and Lundgren O 1976a Colonic blood flow in cat and man as analyzed by an inert gas washout technique *Gastroenterology* **70** 36-44

— 1976b Blood flow in the small intestine of cat and man as analyzed by an inert gas washout technique *Gastroenterology* **70** 45-51

Hulten L, Lindhagen J and Lundgren O 1977 Sympathetic nervous control of intramural blood flow in the feline and human intestines *Gastroenterology* **72** 41-8

Hyman C and Greeson T P 1966 Evidence for the presence of shunts in skin of forearm *J. Invest. Dermatol.* **47** 363-5

Hyman C, Greeson T, Clem M and Winsor D 1964 Capacitance- plethysmograph method for separating blood flow in muscle and skin in the human forearm *Am. Heart J.* **68** 508-14

Hyman C and Wong W H 1968 Capillary filtration coefficient in the extremities of man in high environmental temperatures *Circ. Res.* **22** 251-61

Ikkos K, Ljunggren H and Luft R 1956 Glomerular filtration rate and renal plasma flow in acromegaly *Acta Endocrinol.* **21** 226-36

Ingvar D H, Cronqvist S, Edberg R, Risberg J and Høedt-Rasmussen K 1965 Normal values of regional cerebral blood flow in man, including flow and weight estimates of gray and white matter *Acta Neurol. Scand.* Suppl. **14** 72-8

ICRP 1975 *Reference Man: Anatomical, Physiological and Metabolic Characteristics* Publication 23 (Oxford: Pergamon Press)

ICRP 1988 *Radiation Dose to Patients from Radiopharmaceuticals* Publication 53 (Oxford: Pergamon Press)

Ivarsson L E, Darle N, Hulten L, Lindhagen J and Lundgren O 1982 Gastric blood flow and distribution in anesthetized cat and man as studied by an inert gas elimination method *Scand. J. Gastroenterology* **17** 1025-35

Jelnes R, Astrup A and Bulow J 1985 The double isotope technique for *in vivo* determination of the tissue-to-blood partition coefficient for xenon in human subcutaneous adipose tissue – an evaluation *Scand. J. Clin. Lab. Invest.* **45** 565-8

Johnson J M and Rowell L B 1975 Forearm skin and muscle vascular responses to prolonged leg exercise in man *J. Appl. Physiol.* **39** 920-4

Kaihara S, Van Heerden P D, Migita T and Wagner H N Jr 1968 Measurement of distribution of cardiac output *J. Appl. Physiol.* **25** 696-700

Keiding S 1988 Galactose clearance measurements and liver blood flow *Gastroenterology* **94** 477-81

Kelly P J 1983 *Handbook of Physiology* vol. 3 *Peripheral Circulation and Organ Blood Flow* eds E M Renkin and C C Michel (Bethesda, MD: American Physiological Society) pp 371-96

Kessler B J, Liebler J B, Bronfin G J and Sass M 1954 The hepatic blood flow and splanchnic oxygen consumption in alcoholic fatty liver *J. Clin. Invest.* **33** 1338-45

Kety S S and Schmidt C F 1946 The effects of active and passive hyperventilation on cerebral blood flow, cerebral oxygen consumption, cardiac output, and blood pressure of normal young men *J. Clin. Invest.* **25** 107-19

— 1948 The nitrous oxide method for the quantitative determination of cerebral blood flow in man: Theory, procedure and normal values *J. Clin. Invest.* **27** 476-83

Kirkendall W M, Culbertson J W and Eckstein J W 1959 Renal hemodynamics in patients with coarctation of the aorta *J. Lab. Clin. Med.* **53** 6-21

Kleinerman J and Sancetta S M 1955 Effect of mild steady state exercise on cerebral and general hemodynamics of normal untrained subjects *J. Clin. Invest.* **34** 945-6

Kleinerman J and Sokoloff L 1953 Effects of exercise on cerebral blood flow and metabolism in man *Fed. Proc.* **12** 77

Kolberg A 1959 Relations of renal tubular and glomerular function as influenced by 75 per cent reduction of nephron number *Scand. J. Clin. Lab. Invest.* Suppl. **41** 1-152

Kontos H A, Richardson D W and Patterson J L Jr 1966 Blood flow and metabolism of forearm muscle in man at rest and during sustained contraction *Am. J. Physiol.* **211** 869-76

Krook H 1956 Circulatory studies in liver cirrhosis *Acta Med. Scand.* Suppl. **318** 1-160

Ladefoged J and Pedersen F 1967 Renal blood flow, circulation times and vascular volume in normal man measured by the intraarterial injection – external counting technique *Acta Physiol. Scand.* **69** 220-9

Lahtinen T, Alhava E M, Karjalainen P and Romppanen T 1981 The effect of age on blood flow in the proximal femur in man *J. Nucl. Med.* **22** 966-72

Lahtinen R, Lahtinen T and Romppanen T 1982 Bone and bone-marrow blood flow in chronic granulocytic leukemia and primary myelofibrosis *J. Nucl. Med.* **23** 218-24

Lantz B M T, Foerster J M, Link D P and Holcroft J W 1981 Regional distribution of cardiac output: Normal values in man determined by video dilution technique *Am. J. Roentgenol.* **137** 903-7

Larsen O A and Lassen N A 1967 Fatty tissue blood flow measured by Xe-133 clearance *Scand. J. Clin. Lab. Invest.* Suppl. **99** 46-9

Larsen O A, Lassen N A and Quaade F 1966 Blood flow through human adipose tissue determined with radioactive xenon *Acta Physiol. Scand.* **66** 337-45

Lassen N A 1964 Muscle blood flow in normal man and in patients with intermitted claudication evaluated by simultaneous Xe-133 and Na-24 clearances *J. Clin. Invest.* **43** 1805-12

Lassen N A, Henriksen L, Holm S, Barry D I, Paulson O B, Vorstrup S, Rapin J, le Poncin-Lafitte M, Moretti J L, Askienazy S and Raynaud C 1983 Cerebral blood-flow tomography: Xenon-133 compared with isopropyl-amphetamine-iodine-123 *J. Nucl. Med.* **24** 17-21

Lassen N A and Klee A 1965 Cerebral blood flow determined by saturation and desaturation with krypton-85: An evaluation of the validity of the inert gas method of Kety and Schmidt *Circ. Res.* **16** 26-32

Lassen N A, Lindbjerg J and Munck O 1964 Measurement of blood-flow through skeletal muscle by intramuscular injection of xenon-133 *Lancet* **i** 686-9

Lassen N A and Munck O 1955 The cerebral blood flow in man determined by the use of radioactive krypton *Acta Physiol. Scand.* **33** 32-49

Lassen N A, Roland P E, Larsen B, Melamed E and Soh K 1977 Mapping of human cerebral functions: A study of the regional cerebral blood flow pattern during rest, its reproducibility and the activations seen during basic sensory and motor functions *Acta Neurol. Scand.* Suppl. **64** 262-3

Lauson H D, Bradley S E, Cournand A and Andrews V V 1944 The renal circulation in shock *J. Clin. Invest.* **23** 381-402

Lavender J P, Maseri A, Davies G J, Oliveira B, Sugrue D and Myers M J 1981 The distribution of cardiac output in man recorded by intraventricular injection of microspheres *J. Nucl. Med.* **22** 30

Lee T D Jr, Lindeman R D, Yiengst M J and Shock N W 1966 Influence of age on the cardiovascular and renal responses to tilting *J. Appl. Physiol.* **21** 55-61

Leevy C M, Mendenhall C L, Lesko W and Howard M M 1962 Estimation of hepatic blood flow with indocyanine green *J. Clin. Invest.* **41** 1169-79

Leggett R W and Williams L R 1988 A biokinetic model for Rb in humans *Health Phys.* **55** 685-702

Leiberman D P, Mathie R T, Harper A M and Blumgart L H 1978 An isotope clearance method for measurement of liver blood flow during portasystemic shunt in man *Br. J. Surg.* **65** 578-80

Leight L, DeFazio V, Talmers F N, Regan T J and Hellems H K 1956 Coronary blood flow, myocardial oxygen consumption, and myocardial metabolism in normal and hyperthyroid human subjects *Circulation* **14** 90-9

Lesser G T and Deutsch S 1967 Measurement of adipose tissue blood flow and perfusion in man by uptake of Kr-85 *J. Appl. Physiol.* **23** 621-30

Levy M L, Palazzi H M, Nardi G L and Bunker J P 1961 Hepatic blood flow variations during surgical anesthesia in man measured by radioactive colloid *Surg. Gynecol. Obstet.* **112** 289-94

Lewis B M, Sokoloff L, Wechsler R L, Wentz W B and Kety S S 1960 A method for the continuous measurement of cerebral blood flow in man by means of radioactive krypton (Kr-79) *J. Clin. Invest.* **39** 707-16

Lewis C S Jr, Samuels A J, Daines M C and Hecht H H 1952 Cardiorespiratory, vascular and renal adjustments in cor pulmonale *Circulation* **6** 874-87

Lindbjerg I F 1966 Leg muscle blood-flow measured with xenon-133 after ischaemia periods and after muscular exercise performed during ischaemia *Clin. Sci.* **30** 399-408

Loew F M 1981 *Measurement of Blood Flow. Applications to the Splanchnic Circulation* eds D N Granger and G B Bulkley (Baltimore: Williams and Wilkins) pp 49-55

London G M, Guerin A P, Bouthier J D, London A M and Safar M E 1985 Cardiopulmonary blood volume and plasma renin activity in normal and hypertensive humans *Am. J. Physiol.* **249** H807-13

Lundgren O 1984 *Handbook of Physiology* vol 4 *The Cardiovascular System* ed E M Renkin and C C Michel, (Bethesda, MD: American Physiological Society) pp 799-863

Lundin G 1960 Nitrogen elimination from the tissues during oxygen breathing and its relationship to the fat: muscle ratio and the localization of bends *J. Physiol.* **152** 167-75

Malina R M 1986 *Human Growth* eds F Falkner and J M Tanner (New York: Plenum Press) pp 77-9

Mangold R, Sokoloff L, Conner E, Kleinerman J, Therman P G and Kety S S 1955 The effects of sleep and lack of sleep on the cerebral circulation and metabolism of normal young men *J. Clin. Invest.* **34** 1092-100

Mapleson W W 1963 An electric analogue for uptake and exchange of inert gases and other agents *J. Appl. Physiol.* **18** 197-204

Marcus M L, Bischof C J and Heistad D D 1981 Comparison of microsphere and xenon-133 clearance method in measuring skeletal muscle and cerebral blood flow *Circ. Res.* **48** 748-61

Maxwell M H and Breed E S 1951 The effect of the intravenous administration of pitressin on renal function in man *J. Pharmacol. Exp. Ther.* **103** 190-5

Maxwell M H, Breed E S and Smith H W 1950 Significance of the renal juxtamedullary circulation in man *Am. J. Med.* **9** 216-28

McHenry L C 1964 Quantitative cerebral blood flow determination *Neurology* **14** 785-93

Mellander S and Oberg B 1967 Transcapillary fluid absorption and other vascular reactions in the human forearm during reduction of the circulating blood volume *Acta Physiol. Scand.* **71** 37-46

Mendeloff A I 1954 Effect of intravenous infusions of ethanol upon estimated hepatic blood flow in man *J. Clin. Invest.* **33** 1298-302

Miles B E, De Wardener H E, Churchill-Davidson H C and Wylie W D 1952 The effect on the renal circulation of pentamethonium bromide during anesthesia *Clin. Sci.* **11** 73-9

Mokotoff R, Ross G and Leiter L 1948 Renal plasma flow and sodium reabsorption and excretion in congestive heart failure *J. Clin. Invest.* **27** 1-9

Moreno A H, Burchell A R, Rousselot L M, Panke W F, Slafsky S F and Burke J H 1967 Portal blood flow in cirrhosis of the liver *J. Clin. Invest.* **46** 436-45

Moriyasu F, Ban N, Nishida O, Nakamura T, Koizumi S, Sakai M, Kanematsu Y, Miyake T and Uchino H 1984 Quantitative measurement of portal blood flow in patients with chronic liver disease using an ultrasonic duplex system consisting of a pulsed Doppler flowmeter and B-mode electroscanner *Gastroenterol. Jpn* **19** 529-36

Mottram R F 1955 The oxygen consumption of human skeletal muscle *in vivo J. Physiol.* **128** 268-76

Mottram R F and Brown E 1963 Influence of local cooling on the glucose and oxygen uptake of human forearm muscle *Clin. Sci.* **25** 249-61

Mueller R P, Lynn R B, Sancetta S M, Heckman G and Janouskovec H 1952 Studies of hemodynamic changes in humans following induction of low and high spinal anesthesia: II. The changes in splanchnic blood flow, oxygen extraction and consumption, and splanchnic vascular resistance in humans not undergoing surgery *Circulation* **6** 894-901

Munck O, Andersen A M and Binder C 1967 Clearance of 4-Iodoantipyrine-125-I after subcutaneous injection in various regions *Scand. J. Clin. Lab. Invest.* Suppl. **99** 39-45

Munck O and Lassen N A 1957 Bilateral cerebral blood flow and oxygen consumption in man by use of krypton-85 *Circ. Res.* **5** 163-8

Munnell E W and Taylor H C Jr 1947 Liver blood flow in pregnancy – hepatic vein catheterization *J. Clin. Invest.* **26** 952-6

Myant N B, Pochin E E and Goldie E A G 1949 The plasma iodide clearance rate of the human thyroid *Clin. Sci.* **8** 109-33

Myers J D 1947 The hepatic blood flow and splanchnic oxygen consumption of man – their estimation from urea production or bromsulphalein excretion during catheterization of hepatic veins *J. Clin. Invest.* **26** 1130-7

— 1950 Net splanchnic glucose production in normal man and in various disease states *J. Clin. Invest.* **29** 1421-9

Myers J D, Brannon E S and Holland B C 1950 A correlative study of the cardiac output and the hepatic circulation in hyperthyroidism *J. Clin. Invest.* **29** 1069-77

Nickel J F, Smythe C, Papper E M and Bradley S E 1954 A study of the mode of action of the adrenal medullary hormones on sodium, potassium, and water excretion in man *J. Clin. Invest.* **33** 1687-99

Nielsen S L, Bitsch V, Larsen O A, Lassen N A and Quaade F 1968 Blood flow through human adipose tissue during lipolysis *Scand. J. Clin. Lab. Invest.* **22** 124-30

Nilsson B and Ingvar D H 1967 Intramuscular pressure and contractile strength related to muscle blood flow in man *Scand. J. Clin. Lab. Invest.* Suppl. **99** 31-8

Norryd C, Dencker H, Lunderquist A and Olin T 1974 Superior mesenteric blood flow in man studied with a dye-dilution technique *Acta Chir. Scand.* **141** 109-18

Novack P, Goluboff B, Bortin L, Soffe A, Shenkin H A, Batson P and Golden D 1953 Studies of the cerebral circulation and metabolism in congestive heart failure *Circulation* **7** 724-31

Nylin G, Blomer H, Jones H, Hedlund S and Rylander C 1956 Further studies on the cerebral blood flow estimated with thorium-B-labelled erythrocytes *Br. Heart J.* **18** 385-92

Nylin G, Hedlund S and Regnstrom O 1961 Studies of the cerebral circulation with labeled erythrocytes in healthy man *Circ. Res.* **9** 664-74

Ozolin P 1986 Blood flow in the extremities of athletes *Int. J. Sports Med.* **7** 117-22

Patterson G C and Shepherd J T 1954 The blood flow in the human forearm following venous congestion *J. Physiol.* **125** 501-7

Patterson J L Jr, Heyman A, Battey L L and Ferguson R W 1955 Threshold of response of the cerebral vessels of man to increase in blood carbon dioxide *J. Clin. Invest.* **34** 1857-64

Patterson J L Jr, Heyman A and Duke T W 1951 The cerebral circulation and metabolism in chronic pulmonary emphysema with observations on the effects of inhalation of oxygen *J. Clin. Invest.* **30** 665

Perlmutter J S, Powers W J, Herscovitch P, Fox P T and Raichle M E 1987 Regional asymmetries of cerebral blood flow, blood volume, and oxygen utilization and extraction in normal subjects *J. Cereb. Blood Flow Metab.* **7** 64-7

Peters A M, Klonizakis I, Lavender J P and Lewis S M 1980 Use of Indium-111-labelled platelets to measure spleen function *Br. J. Haematol.* **46** 587-93

Peters A M, Walport M J, Bell R N and Lavender J P 1984 Methods of measuring splenic blood flow and platelet transit time with In-111-labeled platelets *J. Nucl. Med.* **25** 86-90

Pfeiffer J B Jr, Wolff H G and Winter O S 1950 Studies in renal circulation during periods of life stress and accompanying emotional reactions in subjects with and without essential hypertension; observations on the role of neural activity in regulation of renal blood flow *J. Clin. Invest.* **29** 1227-42

Pochin E E 1950 Investigation of thyroid function and disease with radioactive iodine *Lancet* **259** 41-6

Price H L, Deutsch S, Marshall B E, Stephen G W, Behar M G and Neufeld G R 1966 Hemodynamic and metabolic effects of hemorrhage in man, with particular reference to the splanchnic circulation *Circ. Res.* **18** 469-74

Price H L, Kovnat P J, Safer J N, Conner E H and Price M L 1959 The uptake of thiopental by body tissues and its relation to the duration of narcosis *Clin. Pharmacol. Ther.* **1** 16-22

Radigan L R and Robinson S 1949 Effects of environmental heat stress and exercise on renal blood flow and filtration rate *J. Appl. Physiol.* **2** 185-91

Reemtsma K, Hottinger G C, DeGraff A C Jr and Creech O Jr 1960 The estimation of hepatic blood flow using indocyanine green *Surg. Gynecol. Obstet.* **110** 353-6

Regan T J, Timmis G, Gray M, Binak K and Hellems H K 1961 Myocardial oxygen consumption during exercise in fasting and lipemic subjects *J. Clin. Invest.* **40** 624-30

Reichle F A, Sovak M, Soulen R L and Rosemond G P 1972 Portal vein flow determination in the unanesthetized human by umbilicoportal cannulation *J. Surg. Res.* **12** 146-50

Reichman S, Davis W D, Storaasli J P and Gorlin R 1958 Measurement of hepatic blood flow by indicator dilution techniques *J. Clin. Invest.* **37** 1848-56

Reinmuth O M, Scheinberg P and Bourne B 1965 Total cerebral blood flow and metabolism *A.M.A. Arch. Neurol.* **12** 49-66

Renkin E M and Michel C C 1983 *Handbook of Physiology* vol. 3 *Peripheral Circulation and Organ Blood Flow* eds E M Renkin and C C Michel (Bethesda MD: American Physiological Society)

Renkin E M and Michel C C 1984 *Handbook of Physiology* vol. 4 *The Cardiovascular System,* ed E M Renkin and C C Michel (Bethesda MD: American Physiological Society)

Reubi F C, Vorburger C and Tuckman J 1973 Renal distribution volumes of indocyanine green, [Cr-51-] EDTA, and Na-24 in man during acute renal failure after shock *J. Clin. Invest.* **52** 223-35

Reynolds T B, Paton A, Freeman M, Howard F and Sherlock S 1953 The effect of hexamethonium bromide on splanchnic blood flow, oxygen consumption and glucose output in man *J. Clin. Invest.* **32** 793-800

Roberts M F, Wenger C B, Stolwijk J A J and Nadel E R 1977 Skin blood flow and sweating changes following exercise training and heat acclimation *J. Appl. Physiol.* **43** 133-7

Rowe G G 1959 The nitrous-oxide method for determining the coronary blood flow in man *Am. Heart J.* **58** 268-81

Rowe G G, Castillo C A, Maxwell G M and Crumpton C W 1959 Comparison of systemic and coronary hemodynamics in the normal human male and female *Circ. Res.* **7** 728-32

Rusch N J, Shepherd J T, Webb C R and Vanhoutte P M 1981 Different behavior of the resistance vessels of the human calf and forearm during contralateral isometric exercise, mental stress, and abnormal respiratory movements *Circ. Res.* **48** I118-30

Sapirstein L A 1958 Regional blood flow by fractional distribution of indicators *Am. J. Physiol.* **193** 161-8

Scheinberg P, Blackburn I, Rich M and Saslaw M 1953 Effects of ageing on cerebral circulation and metabolism *A.M.A. Arch. Neurol. Psychol.* **70** 77-85

Scheinberg P and Stead E A Jr 1949 The cerebral blood flow in male subjects as measured by the nitrous oxide technique. Normal values for blood flow, oxygen utilization, glucose utilization, and peripheral resistance, with observations on the effect of tilting and anxiety *J. Clin. Invest.* **28** 1163-71

Schenk W G Jr, McDonald J C, McDonald K and Drapanas T 1962 Direct measurement of hepatic blood flow in surgical patients: With related observations on hepatic flow dynamics in experimental animals *Ann. Surg.* **156** 463-71

Sejrsen P 1967a Diffusion processes invalidating the intra-arterial krypton-85 beta-particle clearance method for measurement of skin blood flow in man *Circ. Res.* **21** 281-95

— 1967b Cutaneous blood flow in man studied by freely diffusible radioactive indicators *Scand. J. Clin. Lab. Invest.* Suppl. **99** 52-9

— 1969 Blood flow in cutaneous tissue in man studied by washout of radioactive xenon *Circ. Res.* **25** 215-29

Shackman R, Graber I G and Melrose D G 1953 Liver blood flow and general anesthesia *Clin. Sci.* **12** 307-15

Shaldon S, Chiandussi L, Guevara L, Caesar J and Sherlock S 1961 The estimation of hepatic blood flow and intrahepatic shunted blood flow by colloidal heat-denatured human serum albumin labelled with I-131 *J. Clin. Invest.* **40** 1346-54

Shapiro W, Wasserman A J and Patterson J L Jr 1966 Human cerebrovascular response to combined hypoxia and hypercapnia *Circ. Res.* **19** 903-10

Shenkin H A, Novak P, Goluboff B, Soffe A M, Bortin L, Golden D and Batson P 1953 The effects of aging, arteriosclerosis, and hypertension upon the cerebral circulation *J. Clin. Invest.* **32** 459-65

Shepherd R C and Warren R 1960 Studies of the blood flow through the lower limb of man by the nitrous oxide technique *Clin. Sci.* **20** 99-105

Sherlock S, Bearn A G, Billing B H and Paterson J C S 1950 Splanchnic blood flow in man by the bromsulfalein method: The relation of peripheral plasma bromsulfalein level to the calculated flow *J. Lab. Clin. Med.* **35** 923-32

Shim S S, Mokkhavesa S, McPherson G D and Schweigel J F 1971 Bone and skeletal blood flow in man measured by a radioisotopic method *Can. J. Surg.* **14** 38-41

Shoshenko K A 1975 *Blood Capillaries* (Novosivirsk: Nauka Publishing House)

Siggaard-Andersen J and Bonde Petersen F 1967 Venous occlusion plethysmography and Xe-133 muscle clearance measured simultaneously on the calf in normal subjects *Scand. J. Clin. Lab. Invest.* **19** 106-12

Sirota J H, Baldwin D S and Villarreal 1950 Diurnal variations of renal function in man *J. Clin. Invest.* **29** 187-92

Slaughter O L, Brown H S and Wakim K G 1948 Effects of tetraethylammonium chloride on blood flow in the extremities of man *J. Lab. Clin. Med.* **33** 741-6

Smith H J, Grottum P and Simonsen S 1986 Ultrasonic assessment of abdominal venous return: II. Volume blood flow in the inferior vena cava and portal vein *Acta Radiol. (Diagn.)* **27** 23-7

Smith H W 1958 *The Kidney Structure and Function in Health and Disease* (New York: Oxford University Press)

Smith J H, Robinson S and Pearcy M 1952 Renal responses to exercise, heat and dehydration *J. Appl. Physiol.* **4** 659-65

Smythe C M, Nickel J F and Bradley S E 1952 The effect of epinephrine (USP), l-epinephrine, and l-norepinephrine on glomerular filtration rate, renal plasma flow, and the urinary excretion of sodium, potassium, and water in normal man *J. Clin. Invest.* **31** 499-506

Soderberg U 1959 Temporal characteristics of thyroid activity *Physiol. Rev.* **39** 777-810

Sokoloff L, Mangold R, Wechsler R L, Kennedy C and Kety S S 1955 The effect of mental arithmetic on cerebral circulation and metabolism *J. Clin. Invest.* **34** 1101-8

Strandell T, Erwald R, Kulling K G, Lundbergh P, Marions O and Wiechel K L 1972 Simultaneous determination of portal vein and hepatic artery blood flow by indicator dilution technique in awake man *Acta Med. Scand.* **191** 139-40

Strandell T and Shepherd J T 1962 The effect in humans of increased sympathetic activity on the blood flow to active muscles *Acta Med. Scand.* Suppl. **472** 146-67

Strandell T and Wahren J 1963 Circulation in the calf at rest, after arterial occlusion and after exercise in normal subjects and in patients with intermittent claudication *Acta Med. Scand.* **173** 99-105

Svensson S E, Lomsky M, Olsson L, Persson S, Strauss H W and Westling H 1982 Non-invasive determination of the distribution of cardiac output in man at rest and during exercise *Clin. Physiol.* **2** 467-77

Talbott J H, Pecora L J, Melville R S and Consolazio W V 1942 Renal function in patients with Addison's disease and in patients with adrenal insufficiency secondary to pituitary pan-hypofunction *J. Clin. Invest.* **21** 107-19

Taplin G V 1965 Liver blood flow *Radioisotopes and Circulation* ed G Sevelius (Boston: Little Brown) pp 205-25

Terroux G K, Sekelj P and Burgen A S V 1959 Oxygen consumption and blood flow in the submaxillary gland of the dog *Can. J. Biochem. Physiol.* **37** 5-15

Thomasson B 1957 Cardiac output in normal subjects under standard basal conditions: The repeatability of measurements by the Fick method *Scand. J. Clin. Lab. Invest.* **9** 365-76

Tonnesen K H 1964 Blood-flow through muscle during rhythmic contraction measured by xenon-133 *Scand. J. Clin. Lab. Invest.* **16** 646-54

Tothill P 1984 Bone blood flow measurement *J. Biomed. Eng.* **6** 251-6

Tranquilli W J, Parks C M, Thurmon J C, Benson G J, Koritz G D, Manohar M and Theodorakis M C 1982 Organ blood flow and distribution of cardiac output in nonanesthetized swine *Am. J. Vet. Res.* **43** 895-7

Tygstrup N, Winkler K, Mellemgaard K and Andreassen M 1962 Determination of the hepatic arterial blood flow and oxygen supply in man by clamping the hepatic artery during surgery *J. Clin. Invest.* **41** 447-54

Ueda H, Kitani K, Kameda H, Takeda T, Chiba K, Nagatani M, Yamada H and Iio M 1971 Splenic blood flow in idiopathic portal hypertension in Japan measured by Kr-85 clearance method. *Acta Hepato-splenol.* **18** 28-40

Vanderhoof E R, Imig C J and Hines H M 1961 Effect of muscle strength and endurance development on blood flow *J. Appl. Physiol.* **16** 873-7

Van Dyke D, Anger H O, Parker H, McRae J, Dobson E L, Yano Y, Naets J P and Linfoot J 1971 Markedly increased bone blood flow in myelofibrosis *J. Nucl. Med.* **12** 506-12

Van Dyke D, Dobson E L, Parker H, Lynch J, Nohr M L and Bacaner M 1975 *Radiopharmaceuticals* eds G Subramanian, B A Rhodes, J F Cooper and V J Sodd (New York: Society of Nuclear Medicine) pp 329-42

Vetter H, Falkner R and Neumayr A 1954 The disappearance rate of colloidal radiogold from the circulation and its application to the estimation of liver blood flow in normal and cirrhotic subjects *J. Clin. Invest.* **33** 1594-602

Vroman N B, Buskirk E R and Hodgson J L 1983 Cardiac output and skin blood flow in lean and obese individuals during exercise in the heat *J. Appl. Physiol.* **55** 69-74

Wade O L and Bishop J M 1962 *Cardiac Output and Regional Blood Flow* (Oxford: Blackwell Scientific Publications)

Wade O L, Combes B, Childs A W, Wheeler H O, Cournand A and Bradley S E 1956 The effect of exercise on the splanchnic blood flow and splanchnic blood volume in normal man *Clin. Sci.* **15** 457-63

Wax S H and Peterson N 1967 Measurement of testicular blood flow by intratesticular injection of xenon-133 *Surg. Forum* **18** 544-6

Weinberg S L, Cagirgan C M, Grove G R and Smith G 1964 Measurement of relative coronary blood flow by precordial monitoring *Am. J. Cardiol.* **13** 801-7

Werko L, Ek J, Bucht H and Eliasch H 1952 Correlation between renal dynamics, cardiac output and right heart pressures in mitral valvular disease *Scand. J. Clin. Lab. Invest.* **4** 15-23

Wesson L G 1964 Electrolyte excretion in relation to diurnal cycles of renal function *Medicine* **43** 547-92

— 1969 *Physiology of the Human Kidney* (New York: Grune and Stratton)

White H L and Rolf D 1948 Effects of exercise and of some other influences on the renal circulation in man *Am. J. Physiol.* **152** 505-16

Wiegand B D, Ketterer S G and Rapaport E 1960 The use of indocyanine green for the evaluation of hepatic function and blood flow in man *Am. J. Dig. Dis.* **5** 427-36

Wiggins W S, Manry C H, Lyons R H and Pitts R F 1951 The effect of salt loading and salt depletion on renal function and electrolyte excretion in man *Circulation* **3** 275-81

Wilkins R W, Culbertson J W and Rymut A A 1952 The hepatic blood flow in resting hypertensive patients before and after splanchnicectomy *J. Clin. Invest.* **31** 529-31

Williams C A, Mudd J G and Lind A R 1978 The forearm blood flow during intermittent hand-grip isometric exercise *Circ. Res.* **48** I110-7

Williams L R 1990 (in preparation)

Williams L R and Leggett R W 1987 The distribution of intracellular alkali metals in Reference Man *Phys. Med. Biol.* **32** 173-90

Williams R, Condon R E, Williams H S, Blendis L M and Kreel L 1968 Splenic blood flow in cirrhosis and portal hypertension *Clin. Sci.* **34** 441-52

Winkler K, Larsen J A, Munkner T and Tygstrup N 1965 Determination of the hepatic blood flow in man by simultaneous use of five test substances measured in two parts of the liver *Scand. J. Clin. Lab. Invest.* **17** 423-32

Winkler K and Tygstrup N 1960 Determination of hepatic blood flow in man by cardio green *Scand. J. Clin. Lab. Invest.* **12** 353-6

Wootton R, Reeve J and Veall N 1976 The clinical measurement of skeletal blood flow *Clin. Sci. Mol. Med.* **50** 261-8

Wyper D J, Lennox G A and Rowan J O 1976 Two minute slope inhalation technique for cerebral blood flow measurement in man. 2. Clinical appraisal *J. Neurol. Neurosurg. Psychiatry* **39** 147-51

Yurchak P M, Ellis R L, Cohen L S and Gorlin R 1964 Effects of norepinephrine on the coronary circulation in man *Circulation* **30** 180-7

Zelis R, Longhurst J, Capone R J and Mason D T 1974 A comparison of regional blood flow and oxygen utilization during dynamic forearm exercise in normal subjects and patients with congestive heart failure *Circulation* **50** 137-43

Zelis R, Meson D T and Brounwold E 1969 Partition of blood flow to the cutaneous and muscular beds of the forearm at rest and during leg exercise in normal subjects and in patients with heart failure *Circ. Res.* **24** 799-806

Zobl E G, Talmers F N, Christensen R C and Baer L J 1965 Effect of exercise on the cerebral circulation and metabolism *J. Appl. Physiol.* **20** 1289-93