Supporting technologies

© RWD Nickalls,
Department of Anaesthesia,
Nottingham University Hospitals,
City Hospital Campus,
Nottingham, UK.

dick@nickalls.org
www.nickalls.org

9 Supporting technologies 133
9.1 Serendipity 133
9.2 Tuohy needle with Huber point and Lee markings . . 135
9.3 Pulse oximetry 136
9.4 MAC 138
9.4.1 History 138
9.4.2 Age-corrected MAC 143
9.4.3 Temperature corrected MAC 149
9.4.4 Dosage and MAC correction 149
9.4.5 References 153
9.5 Arterial line 158
9.5.1 History 158
9.5.2 Anatomy 159
9.5.3 Allen test 160
9.5.4 Systolic pressure variation 162
9.5.5 Complications . . 162
9.6 Central venous catheter . . 163
9.6.1 History 163
9.6.2 References 166
9.6.3 Optimum position 168
9.6.4 Anatomy 168
9.6.5 Position of CVP tip 169
9.6.6 General 170
9.6.7 Ultrasound guided . 171
9.6.8 External jugular vein 172
9.6.9 Axillary vein . . . 172
9.6.10 Femoral vein . . . 173
9.6.11 Complications . . 174
9.7 Pulmonary artery catheter . 175
9.7.1 History 175
9.7.2 Decline in use . . . 178
9.8 Computers & information technology 179
9.8.1 History of the anaesthesia record . . 179
9.8.2 The anaesthesia workstation 181
9.8.3 References 183

FROM: Nickalls RWD. *Notes on thoracic anaesthesia*
http://www.nickalls.org/dick/papers/thoracic/book-thorax.pdf
REVISION: March 2011

9 Supporting technologies[1]

HERE we address some of the supporting technologies associated with thoracic anaesthesia. The motivation is historical—to highlight some of the key references and see how discoveries were made.[2] Time spent reading the original papers and early documentation is usually well rewarded, often revealing the hand of serendipity. The overview of thoracic anaesthesia by Brodsky [3] (2005) is a useful starting point.

Two insights are commonly cited as influencing discovery and subsequent innovative development. The first is awareness of the problem, immortalised by Louis Pasteur (1822–1895) in the succinct but misquoted phrase *Chance favours the prepared mind.*[4] The second is appreciating the significance of a discovery. For example, although Crawford Long (1815–1878) was the first person to use ether for a surgical operation, we really owe the initial development of clinical anaesthesia to William Morton[5] (1819–1868) who appreciated its value to humanity, and to John Snow (1813–1858) who laid the scientific foundations of inhalational anaesthesia.[6]

9.1 Serendipity

The word serendipity is often used in the context of discovery and innovation; its original usage was very specific—discovering, quite by accident, something that you were *not*

[1] `http://www.nickalls.org/dick/papers/thoracic/hand-support.pdf`

[2] See the memorable September 2002 issue of the ASA Newsletter (`http://www.asahq.org/nlindex.html`) on the history of monitoring (included on the thoracic CD).

[3] Brodsky JB (2005). The evolution of thoracic anesthesia. *Thoracic Surgery Clinics*; 15, 1–10.

[4] The full sentence actually used by Pasteur in his inaugural address (1854) as the professor of chemistry at the Faculté des Sciences at Lille, was *In the field of observation, chance only favours those minds which have been prepared.* (Mackay A (1977). *The harvest of a quiet eye; a selection of scientific quotations.* Institute of Physics, London; ISBN 0-85498-031-8. page 116.)

[5] It now appears that there were in fact several other people experimenting with ether at that time (see Stone, Meyer and Alston 2010).

[6] See more on John Snow in Section 9.4.1.

looking for (Remer 1965). The word is ascribed to Horace Walpole (1717–1797), who used it in 1754 in a letter [7] to Horace Mann, then living in Florence (Toynbee 1903; Remer 1965, Boyle 2000).

> I must tell you of a critical discovery of mine *à propos*: in an old book of Venetian arms there are two coats of Capello, who from their *name* bear a *hat*, on one of them is added a flower-de-luce on a blue ball, which I am persuaded was given to the family by the Great Duke, in consideration of this alliance; the Medicis you know bore such a badge at the top of their own arms; this discovery I made by a talisman, which Mr Chute calls the *sortes Walpolitaniæ*, by which I find everything I want *à point nommé* wherever I dip for it. This discovery indeed is almost of that kind I call *serendipity*, a very expressive word, which as I have nothing better to tell you, I shall endeavour to explain to you: you will understand it better by the derivation than by the definition. I once read a silly fairy tale, called *The three princes of serendip*:[8] as their highnesses travelled, they were always making discoveries, by accidents and sagacity, of things which they were not in quest of: for instance, one of them discovered that a mule [9] blind of the right eye had travelled the same road lately, because the grass was eaten only on the left side, where it was worse than on the right—now do you understand *serendipity*? One of the most remarkable instances of this *accidental sagacity* (for you must observe that *no* discovery of a thing you *are* looking for, comes under this description) was of my Lord Shaftsbury, who happening to dine at Lord Chancellor Clarendon's, found out the marriage of the Duke of York and Mrs Hyde, by the respect with which her mother treated her at table.
>
> Horace Walpole — January 28, 1754
> *From*: Toynbee (1903)

The animal in the original story was actually a camel. The relevant extract from the 1964 English translation of the 1557 Italian version (Boyle 2000), runs as follows.

> Misfortune befalls the princes when a camel driver stops them on the road and asks them if they have seen one of his camels. Although they have not, they have noticed signs that suggest a camel has passed along the road. Ever ready to dazzle with their wit and sagacity, the princes mystify the camel driver by asking him if the lost camel is blind in one eye, missing a tooth and lame. The camel driver, impressed by the accuracy of the description, immediately hurries off in pursuit of the animal.
>
> After a fruitless search, and feeling deceived, he returns to the princes, who reassure him by supplying further information. The camel, they say, carried a load of butter on one side and honey on the other, and was ridden by a pregnant woman. Concluding that the princes have stolen the camel, the driver has them imprisoned. It is only after the driver's neighbour finds the camel that they are released.
>
> The princes are brought before the Emperor Beramo, who asks them how they could give such an accurate description of a camel they have never seen. It is clear from the

[7] Letter dated 28 January, 1754—see Toynbee (1903).
[8] Sri Lanka.
[9] A camel in the English version.

> princes' reply that they had brilliantly interpreted the scant evidence observed along the road.
>
> As the grass had been eaten on one side of the road where it was less verdant, the princes deduced that the camel was blind on the other side. Because there were lumps of chewed grass on the road the size of a camel's tooth, presumably they had fallen through the gap left by a missing tooth. The tracks showed the prints of only three feet, the fourth being dragged, indicating that the animal was lame. That butter was carried on one side of the camel and honey on the other was clear because ants had been attracted to melted butter on one side of the road and flies to spilled honey on the other.
>
> Boyle (2000)

- Boyle R (2000). *The three princes of Serendip.* http://livingheritage.org/three_princes.htm [downloaded June 2006]
- Garrett AB (1963). *The flash of genius.* (D. Van Nostrand Company, Inc., Princeton, New Jersey, USA) pp. 239–240.
- Remer TG (1965). *Serendipity and the three princes: from the* PEREGRINAGGIO *of 1557* (University of Oklahoma Press, Norman, Oaklahoma, USA). [includes an English translation of the 1557 *Peregrinaggio* edition]
- Toynbee P (1903). *Letters of Horace Walpole*; arranged by Mrs. Paget Toynbee. (The Clarenden Press, Oxford, UK). See letter dated: 28 January, 1754.

  Walpole's letters (Ed. P Cunningham, 4 vols) are available on the *Project Gutenberg* website (http://www.gutenberg.org/). For the letter of 28 January 1754 (to Horace Mann) see letter 90, Volume 2 (1749–1759), pages 203–205:

9.2 Tuohy needle with Huber point and Lee markings

Not only is the modern epidural needle a fusion of three primary ideas, but it actually started life as spinal needle. Of the many designs which have been developed few have endured (see the excellent review by Frölich *et al.* 2001).

Edward Boyce Tuohy (1908–1959) was an anaesthetist at the Mayo Clinic (Rochester, Minnesota, USA), interested in continuous spinal anaesthesia (Maltby 2002). Although this technique was first described by Henry Dean in 1906, it was mainly developed during the 1940s by William Lemmon (Maltby, 2002). However Lemmon's technique was far from ideal since it required the needle to remain in position (tip in the CSF) during anaesthesia in order to allow intermittent top-ups as required.

Tuohy's idea was to develop a method of introducing a catheter into the lumbar CSF space via a spinal needle to facilitate continuous spinal anaesthesia—the needle itself could then be removed once the catheter was in place. Continuous caudal anaesthesia via a caudal catheter was already fairly widely used, and lumbar subarachnoid catheters were also sometimes used for drainage in meningitis.

In 1944 Tuohy described this technique using an ordinary 15-gauge spinal needle (Maltby 2002), and only later, in 1945, did he decide to incorporate the Huber point (designed by Ralph L Huber (1890–1953) and made by Becton Dickinson) taking advantage of its lateral opening which allowed the catheter to be directed sideways into the space (Tuohy 1945). In 1949, both MM Curbelo and Charles Flowers described using the Tuohy needle for epidural anaesthesia. Tuohy was later appointed professor of anaesthesia at the Georgetown Medical Centre in Washington, DC.

Finally, we owe the 1 cm markings on the standard Tuohy needle to the English anaesthetist John Alfred Lee (1906–1989). He added them so that anaesthetists would know fairly accurately the depth of the needle tip, and hoped that this small refinement might reduce the number of dural taps (Lee 1960; Maltby 2002).

- Eldor J (1995). Huber needle and Tuohy catheter. *Regional Anesthesia*; 20, 252–253 [cited from Maltby 2002]
- Frölich MA and Caton D (2001). Pioneers in epidural needle design. *Anesthesia and Analgesia*; 93, 215-220.
- Lee JA (1960). Specially marked needle to facilitate epidural block. *Anaesthesia*; 15, 186. [cited from Maltby 2002]
- Maltby JR (2002). *Notable names in anaesthesia.* (The Royal Society of Medicine Press Limited, London). [JA Lee (pp. 114–116); EB Tuohy (pp. 216–218)]
- Schorr MR (1966). Needles: some points to think about Part II. *Anesthesia and Analgesia*; 45, 514–519 [cited from Maltby 2002]
- Tuohy EB (1945). Continuous spinal anesthesia: a new method utilizing a ureteral catheter. *Surgical Clinics of North America*; 25, 834–840 [cited from Maltby 2002]

9.3 Pulse oximetry

For a detailed review of the long and and fascinating history of blood gases, oximetry and pulse oximetry see Severinghaus (2002; 1986) and Severinghaus and Astrup (1987).

The first practical oximeter was the eight-wavelength ear-oximeter developed in 1964 by Robert Shaw and subsequently marketed by Hewlett-Packard in 1970 (Moyle 1994). In 1971 Takuo Aoyagi (1936–), a Japanese biomedical engineer at the Nihon Kohden Corporation (Tokyo), used the pulsatility of the absorption signal to separate arterial and tissue absorption and determine arterial saturation. Severinghaus describes it thus:

> Takuo Aoyagi ... attempted to eliminate arterial pulsatile 'noise' in his earpiece dye dilution curves by subtracting infra-red signals. He observed that the compensated noise varied with oxygen saturation and realised that it might be used to compute the arterial oxygen saturation.
>
> Severinghaus (1989)

The first commercial pulse oximeter appeared in 1970 (Moyle 1994), and in 1982 the Stanford anaesthetist William New (1942–), with Jack Lloyd and engineer Jim Corenham, founded *Nellcor* [10] *Incorporated* to mass-produce clinically useful pulse-oximeters (Rendall-Baker and Bause 2002).

If a finger pulse-oximeter fails owing to significant peripheral vasoconstriction, then an ear-probe will usually be satisfactory. Alternatively, a digital nerve block may help (Erasmus 2003).

- Astrup PB and Severinghaus JW (1986). *History of blood gases, acids and bases.* (Munksgaard, Copenhagen). [from Severinghaus 1989]
- Breathnach CS (1972). The development of blood gas analysis. *Medical History*; 16, 51–62. (available from http://www.pubmedcentral.gov/)
- Erasmus PD (2003). Digital block improves pulse oximetry signal in vasoconstricted patients. *Anaesthesia*; 58, 1033–1034.
- Kofke WA (2003). An interview with John W. Severinghaus. *Association of University Anesthesiologists (AUA) Update*; Fall 2003 issue. http://www.auahq.org/fall03aua.pdf [an interesting 4 page article in which Severinghaus describes how he became involved in MAC, blood gases and oximetry]
- Moyle JTB (1994). *Pulse oximetry.* (BMJ Publishing Group, London).
- Pole Y (1999). Evolution of the pulse-oximeter. *The History of Anaesthesia Society Proceedings*; 26, 21–22.
- Rendell-Baker L and Bause GS (2002). Cardiorespiratory monitoring: a pictorial sampler. *ASA Newsletter*; 66, No. 9 (September) (http://www.asahq.org/Newsletters/2002/)
- Severinghaus JW (2002). The history of clinical oxygen monitoring. In: Eds. Diz JC, Franco A, Bacon DR, Rupreht J and Alvarez J. *The History of Anesthesia. Proceedings of the Fifth International Symposium on the History of Anesthesia; Santiago, Spain, 19–23 September 2001.* Excerpta Medica, International Congress Series 1242. ISBN:0-444-51293-4 (Elsevier Science). pp. 115–120.
- Severinghaus JW and Astrup PB. (1987). History of blood gas analysis. *International Anesthesiology Clinics*; 25, no. 4, (Little, Brown & Co.., Boston, USA). [first published as a series of articles in *Journal of Clinical Monitoring* in 1986]
- Severinghaus JW (1986). Historical development of oxygenation monitoring. In: *Pulse Oximetry.* Eds. Payne JP & Severinghaus JW, (Springer-Verlag), pp. 1–18 [covers spectroscopy, oximetry and blood gas electrodes]

[10] The name 'Nellcor' was derived from a synthesis of the surnames NEw, LLoyd, CORenham (Rendall-Baker and Bause 2002).

- Severinghaus JW and Astrup PB. (1986). History of blood gas analysis. VI. Oximetry. *Journal of Clinical Monitoring*; 2, 270–288.
- Severinghaus JW and Honda Y. (1987). History of blood gas analysis. VII. Pulse oximetry. *Journal of Clinical Monitoring*; 3, 135–138.
- West JB (1998). *High life; a history of high-altitude physiology and medicine.* (Oxford University Press).
- Yoshiya I, Shimada Y and Tanaka K (1980). Spectrophotometric monitoring of arterial oxygen saturation in the fingertip. *Med. Biol. Eng. Comput.*; 18, 27–32. [excellent]

9.4 MAC

Ether contributes other benefits besides preventing the pain.
It keeps patients still, who otherwise would not be.

John Snow
From: Eger (1974),[11] p. 1

9.4.1 History

John Snow

John Snow (1813–1858) appears to have been the first person to appreciate the importance of controlling the inspired concentration of volatile anaesthetics, and within five years of William Morton's ether demonstration [12] he had single-handedly established the scientific foundations underpinning the pharmacokinetics of volatile anaesthetics.

Snow was a London-based GP with hospital connections, and had been interested for a long time in the use of inhalation agents on respiration. He initially investigated the use of carbon dioxide, and had been experimenting with inhaled ether since 1843 believing it to be a useful medicine for improving circulation. In 1846 he published an article entitled "*Pathological effects of atmospheres*" (Maltby 2002; Vinten-Johansen *et al.* 2003).

Consequently, following Morton's ether demonstration (October 16, 1846) at the Massachusetts General Hospital (Boston, USA), and the subsequent demonstration in London in December 1846, Snow found himself in the right place at the right time. Furthermore, with his interest in chemistry and recent researches into inhaled ether he also found himself to be just the right person to get involved in this new anaesthesia phenomenon. Since his GP work was not very profitable, Snow decided to take up anaesthesia.

Snow was extraordinarily industrious and productive. By mid 1847 he had (a) defined and published the temperature characteristics of ether vapour (January 1947), (b) designed

[11] This quotation, which heads Eger's own chapter on MAC, is from: Snow 1847 (part 4).

[12] William Morton (1819–1868) gave his demonstration on October 16, 1846. For an excellent account of the history and background see MacQuitty (1969).

an ether inhaler, (c) defined a range of clinical stages of anaesthesia (his five 'degrees of narcotism'), and (d) performed many animal experiments with a view to determining the effects of different inspired concentrations of both ether and chloroform. Snow appreciated the significance of knowing the saturated vapour pressure, and went on to show that the amount of volatile agent required to produce anaesthesia was inversely related to its solubility in the blood.

Snow published his findings in an eighteen-part series of articles in the journal *London Medical Gazette* during the period 1848 to 1851, entitled "On narcotism by the inhalation of vapours". In the following extracts (all from Part–I of the series) Snow describes the effects on a mouse of a sequence of step increases in the inspired concentration of ether (from approximately 1·2 % to 4·7 %).[13] Notice the detail of his observations, and how he pays particular attention to how well the mouse breathes (I have added a calculated concentration in $\mathrm{MAC}^{ether}_{mouse}$ at each stage to make it easier to follow his experiments).

> I consider, however, that I have found a plan of determining more exactly the [required] proportion of ether and of other volatile substances present in the blood in the different degrees of narcotism. It consists of ascertaining the most diluted mixture of vapour and of air that will suffice to produce any particular amount of narcotism; and is founded on the following considerations, and corroborated by its agreeing with the comparative physiological strength of the various substances.
>
> ... The plan which I adopted to ascertain the smallest quantity of vapour, in proportion to the air, that would produce a given effect, was to weigh a small quantity of the volatile liquid in a little bottle, and introduce it into a large glass jar covered with a plate of glass; and having taken care that the resulting vapour was equally diffused through the air, to introduce an animal so small, that the jar would represent a capacious apartment for it, and wait for that period when the effects of the vapour no longer increased. ...
>
> Exp. 17. — Two grains of ether were put into a jar holding 200 cubic inches [1·16 %, 0·36 MAC], and the vapour diffused equally, when a tame mouse was introduced, and allowed to remain a quarter of an hour, but it was not appreciably affected.
>
> Exp. 18. — Another mouse was placed in the same jar, with three grains of ether, being a grain and a half to each 100 cubic inches [1·75 %, 0·55 MAC]. In a minute and a half it was unable to stand, but continued to move its limbs occasionally. It remained eight minutes without becoming further affected. When taken out it was sensible to pinching, but fell over on its side in attempting to walk. In a minute and a half the effect of the ether appeared to have gone off entirely.
>
> Exp. 19. — A white mouse in the same jar, with four grains of ether [2·33 %, 0·72 MAC], was unable to stand at the end of a minute, and at the end of another minute ceased to move, but continued to breath naturally, and was taken out at the end of five minutes. It moved on being pinched, began to attempt to walk at the end of a minute, and in two minutes more seemed quite recovered.

[13] $\mathrm{MAC}^{ether}_{mouse} = 3{\cdot}2\,\%$ (Eger 1974, p. 5).

Exp. 20. — Five grains of ether, being two and a half grains to each 100 cubic inches [2·92 %, 0·91 MAC], were diffused throughout the same jar, and a mouse put in. It became rather more quickly insensible than the one in the last experiment. It was allowed to remain eight minutes. It moved its foot a very little when pinched, and recovered in the course of four minutes.

Exp. 21. — A white mouse was placed in the same jar with six grains of ether [3·5 %, 1·1 MAC]. In a minute and a half it was lying insensible. At the end of three minutes the breathing became laborious, and accompanied by a kind of stertor. It continued in this state till taken out, at the end of seven minutes, when it was found to be totally insensible to pinching. The breathing improved at the end of a minute; it began to move at the end of three minutes; and five minutes after its removal it had recovered.

Exp. 22. — The same mouse was put into this jar on the following day, with seven grains of ether, being 3·5 grs to the 100 cubic inches [4·08 %, 1·28 MAC]. Stertorous breathing came on sooner than before; it seemed at the point of death when four minutes had elapsed; and being then taken out, was longer in recovering than after the last experiment.

Exp. 23. — Two or three days afterwards the same mouse was placed in the jar, with eight grains of ether, being 4 grains to the 100 cubic inches [4·66 %, 1·46 MAC]. It became insensible in half a minute. In two minutes and a half the breathing became difficult, and at a little more than three minutes it appeared that the breathing was about to cease, and the mouse was taken out. In a minute or two the breathing improved, and in the course of five minutes from its removal it had recovered.

... We find from the eighteenth experiment, that a grain and a half of ether for each 100 cubic inches of air, is sufficient to induce the second degree of narcotism in the mouse; and a grain and a half of ether make 1·9 cubic inches of vapour, of sp. gr. 2·586. Now the ether I employed boiled at 96 °[F].[14] At this temperature, consequently, its vapour would exclude the air entirely; and the ether vapour in contact with the liquid giving it off, could only be raised to 100° by such a pressure as would cause the boiling point of the ether to rise to that temperature. That pressure would be equal to 32·4 inches of mercury [1·082 Atm.], or 2·4 inches above the usual barometrical pressure; and the vapour would be condensed somewhat, so that the space of 100 cubic inches [at 1·082 Atm.] would contain 108 cubic inches at the usual pressure [1 Atm.]. This is the quantity, then, with which we have to compare 1·9 cubic inches, in order to ascertain the degree of saturation of the space in the air-cells of the lungs, and also of the blood; and by calculation, as when treating of chloroform,

1·9 is to 108 as 0·0175 is to 1

So that we find 0·0175 [1·75 %], or 1/57th, to be the amount of saturation of the blood by ether necessary to produce the second degree of narcotism;

Snow (1848a)

[14] 96 °F = 35·5 °C. ($\frac{F-32}{9} = \frac{C}{5}$). Pure diethyl-ether boils at 34·51 °C (CRC Handbook of chemistry and physics; 1972).

Notice the interesting way in which Snow calculates the vapour concentration resulting from 1·5 grains [15] of liquid diethyl-ether [16] in 100 cubic inches [17] of air at 100°F [18] as 1·75 %. My own calculation runs as follows. Since the molecular weight of diethyl-ether is 74·12, the volume of pure ether vapour at STP occupied by 96·75 mg liquid ether (1·5 grains) is given by [19]

$$22{\cdot}4 \times \frac{96{\cdot}75}{74{\cdot}12} = 29{\cdot}24\,\text{cc}$$

If we now correct this volume for a temperature of 100°F [20] (37·7°C) we obtain $29{\cdot}24 \times 310{\cdot}7/273 = 33{\cdot}3$ cc. Adding this volume of pure vapour to 100 cubic inches of air [21] (also at 37·7°C) gives a concentration of

$$\frac{33{\cdot}3}{33{\cdot}3 + (100 \times 2{\cdot}54^3 \times 310{\cdot}7/273)} = 0{\cdot}01754 \equiv 1{\cdot}75\ \%$$

However, we have made some simplifying assumptions (e.g., constant pressure and complete mixing), and since Snow only used a glass jar with a simple lid, it is likely that some of the mixture escaped from the jar before mixing was complete.[22]

It is clear from these extracts from Snow's publications, that Snow was seeking the inspired concentration associated with each of his five 'degrees of narcotism', and that he was guided by two key principles, namely (a) to determine 'the most diluted mixture' which gave these effects (i.e., the minimum concentration), and (b) waiting until 'the effect no longer increased' (i.e., at equilibrium).

Snow's pharmacological approach of linking particular inspired concentrations of vapour to particular states or depths of anaesthesia, and then using this information to try and deliver a safer form of anaesthesia by controlling the inspired vapour concentration was, therefore, strikingly similar to our modern use of MAC.[23] His experiments were carefully performed, observed, and well documented—in fact so much so that they even allow us to make a reasonably accurate estimate of MAC for the mouse. For example, Snow's experiments 20 and 21 suggest that the inspired concentration of ether associated with 50 % movement was between 2·9 % and 3·5 %, giving an estimate close to the modern value of $\text{MAC}^{ether}_{mouse}$ for the mouse [24] of 3·2 %.

[15] 1 grain = 64·5 mg.

[16] $CH_3\,CH_2\,O\,CH_2\,CH_3$; molecular weight = 74·12; BP = 34·51° C

[17] 1 cubic inch = $2{\cdot}54^3 = 16{\cdot}38$ cc.

[18] 100°F = 37·7°C.

[19] 1 gm mol of vapour occupies 22·4 L at STP.

[20] Note that this is roughly mouse body temperature.

[21] We keep the pressure constant and assume complete mixing.

[22] Please email me if you improve on this analysis.

[23] The first paper on MAC was by Merkel and Eger (1963). The definition of MAC is as follows:– the minimum alveolar concentration, at equilibrium, and at 1 atmosphere pressure, which prevents movement in 50 % of patients to a standard surgical incision. For an excellent early overview of MAC see Chapter 1 in the timeless classic book by Eger (1974).

[24] Eger (1974), p. 5.

100 years or so later in the early 1960s Eger and Severinghaus embodied Snow's concepts in the form of MAC (Merkel and Eger 1963; Saidman and Eger 1964; Eger, Saidman, and Brandstater 1965a).

Edmond Eger

In 1960 Edmond Eger joined the San Francisco Department of Anaesthesia, and became a 'Research Fellow' to John Severinghaus (Eger 2002, Maltby 2002). Eger and Dr Giles Merkel (Research Fellow) were given the task of defining the properties of a new volatile anaesthetic agent called halopropane. Eger describes the early steps as follows.

> From studies John [Severinghaus] and others had performed with carbon dioxide, we knew that measuring the end-tidal concentration of a gas gave us a handle on the arterial partial pressure for that gas. Also, the work of Kety and Schmidt indicated that the cerebral partial pressure of an inert gas should rapidly equilibrate with the partial pressure in arterial blood. So, if we measured the end-tidal concentration of halopropane and held it stable for a sufficient period of time, the end-tidal concentration would give us a measure of the anesthetic partial pressure at its site of action. With that, we had the first part of MAC.
>
> The second part was not hard to come by. ... Movement. A categorical response, seemed just the thing ... So we married the end-tidal concentration with movement–no movement as an index of anesthesia, and MAC was born.
>
> Everything except the name. John's group met every Monday morning to discuss the previous week's work and what might be done in the coming week ... At one of these Giles and I told of our technique for determining the minimal alveolar anesthetic concentration, and John connected this to the ratio of the speed of an airplane relative to the speed of sound (a MAAC ratio). John now says it never was clear why we chose MAC rather than MAAC. I don't remember either, except that we wanted to emphasise the word "alveolar". Besides, voicing "MAAC" might make us sound like bleating sheep rather than anesthesiologists.
>
> The next step was to determine MAC in humans. ... The result was the series of articles that were published in 1965 (Eger, Saidman and Brandstater 1965a, 1965b; Eger *et al.* 1965).
>
> Eger (2002)

John Severinghaus

Severinghaus (Severinghaus 2009, Maltby 2002) recalled this episode in a recent journal interview as follows (Kofke 2003).

> Dr. Eger was interested in the relative potency of anesthetics. He wanted a way to compare them numerically in terms of their alveolar concentrations at the time of establishment of a minimal level of anesthesia to permit surgery. It was clear to all that for each patient or animal, there was a critical alveolar (and thus arterial and ultimately brain) pressure of an agent that just prevented a motor response to pain. He

> believed this would be a relatively invariant number between patients This would be the minimal alveolar anesthetic concentration. I recalled that in aviation, a similar index, Mach, was the ratio of an aircraft's speed to the speed of sound.[25] A hypersonic flight was defined, for example, as Mach 2, twice the speed of sound. I suggested the same symbol be used for the ratio of concentration of the anesthetic in the alveoli (as determined in the airway at end expiration) to that critical no-movement level, which would be defined as 1 MAC, originally MAAC. It still should be MAAC since we can't agree on whether the single 'A' refers to alveolar or anesthetic or both.
>
> Kofke (2003)

William Mapleson

In 1979, a far-sighted William Mapleson anticipated the increasingly central role of MAC with respect to how anaesthetists delivered a given depth of anaesthesia, as follows (see also Maltby 2002).

> ... To this end, the anaesthetist will be invited to set his flows of oxygen and nitrous oxide in the normal way and then to set the brain tension of anaesthetic he requires, not in kPa or mmHg, but in total MAC units.
>
> Mapleson (1979).

More recently the clinical utility of MAC has been extended by establishing its variation with age (Mapleson, 1996), temperature (Eger 2001) and hair colour (Liem *et al.* 2004).

9.4.2 Age-corrected MAC

Although several factors are known to be associated with altered anaesthetic requirements,[26] age is the most important owing to the increasingly large age-range met with in clinical practice.

While age has long been known to influence anaesthetic requirement (Gregory, Eger and Munson 1969), the exact variation of MAC with age was formalised only recently by Mapleson (1996), following a meta-analysis of the available data (see Table 9.1). In particular, Mapleson showed that semi-log plots of MAC against age (age $\geq$ 1 year) for all inhalational agents are linear and parallel, and hence it is probable that all the inhalational agents achieve their effects by a similar mechanism. On this basis, therefore, Mapleson derived the following relationship between age and MAC from the pooled data,

$$\mathrm{MAC}_{age} = \mathrm{MAC}_{40} \times 10^{-0{\cdot}00269(age-40)}$$

which expresses MAC for a given age as a function of that at 40 years (MAC_{40}).

The computed real-time MAC as displayed by the Datex AS/3 and S/5 anaesthesia monitors relates to normothermic patients aged approximately 35 years-old. However,

[25] Severinghaus worked on radar technology during World War II (Kofke 2003).

[26] The key factors are narcotics (see section on remifentanil in the appendix), age, temperature, pregnancy, and hair colour (Liem *et al.* 2004, showed that patients with red hair had a 19 % increased MAC requirement).

Table 9.1:
MAC data based on age $\geq$ 1 year. The 95 % confidence limits (CL) for ages 1 and 80 years are up to 1 % greater than at MAC_{40} (from Mapleson 1996). * For the CO_2 value see Eisele and Eger (1967).

Agent	1 year	40 years	80 years	95 % CL ($\pm$ % MAC_{40})
Halothane	0·95	0·75	0·58	6
Isoflurane	1·49	1·17	0·91	6
Enflurane	2·08	1·63	1·27	17
Sevoflurane	2·29	1·80	1·40	6
Desflurane	8·3	6·6	5·1	10
Carbon dioxide*	—	$\approx$ 30	—	—
Xenon	92	72	57	16
Nitrous oxide	133	104	81	8

since many of the thoracic patients are quite elderly it is more appropriate clinically to use an age-corrected MAC. A real-time software version which incorporates nitrous oxide is shown in Figure 9.5 (page 151). Print versions [27] in the form of graphs which allow for nitrous oxide use have been designed (Nickalls and Mapleson 2003), a separate chart being used for each volatile agent as shown in Figures 9.1–9.3. The use of nitrous oxide is accommodated in the charts by offsetting the right-hand N_2O scales vertically by the amount given by

$$F\mathrm{E}'_{\mathrm{N_2O}} \times \frac{\mathrm{MAC}_{age,\,volatile}}{\mathrm{MAC}_{age,\,\mathrm{N_2O}}}.$$

The print versions are available in Allman and Wilson (2006). A nomogram by Lerou (2004) also gives age-corrected MAC.

Software

The iso-MAC information is also available for some hand-held devices, for example, as the software *MACpalm* and *ACTc*.
MACpalm: The MACpalm program is available from http://www.medicaldownload.com/medicalsoftware/macpalm.html. The installation is described in the MACpalm manual.
ACTc: The Anesthesia Clinical Tutor and Calculator (ACTc) program is available from http://www.gasshead.com/. A manual is available at http://www.gasshead.com/content/TutorACTc.pdf

[27] Allows anyone to confidently use the common volatile agents with patients of any age without any guesswork or the need for superhuman memory. The motivation for developing a convenient graphic version arose from my wanting a paper-equivalent for use when working at another hospital, since I then had no access to my own real-time computer version based in the thoracic theatre at the City Hospital.

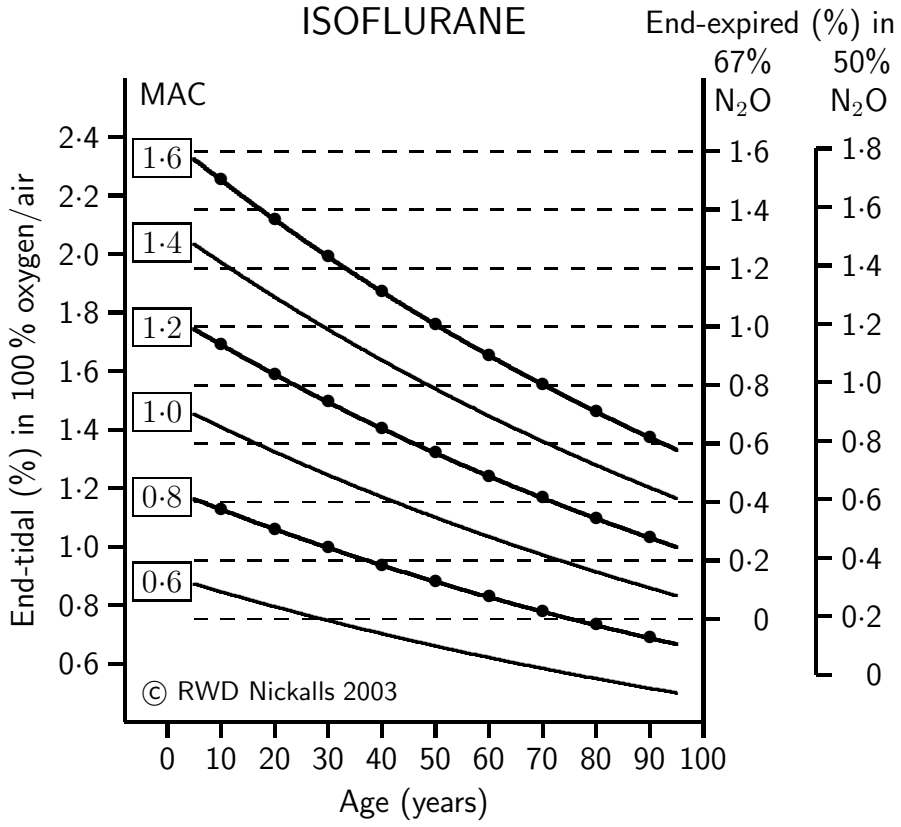

Figure 9.1:
Age-related iso-MAC curves drawn using the data of Mapleson (1996), The dots on the iso-MAC curves are to help alignment. The left-hand ordinate scale indicates the end-expired isoflurane concentration when using an oxygen/air mixture. The two right-hand ordinate scales indicate the end-expired isoflurane concentration when using nitrous oxide 50 % and 67 % in oxygen. The vertical shifts for the nitrous oxide 50 % and 67 % scales are 0·56 and 0·75 respectively. For a given age and MAC the associated end-expired isoflurane concentration is read from the appropriate ordinate scale. For example, a MAC of 1·2 for a 60-year old patient using isoflurane and nitrous oxide 67 % in oxygen requires an end-expired isoflurane concentration of approximately 0·5 %.

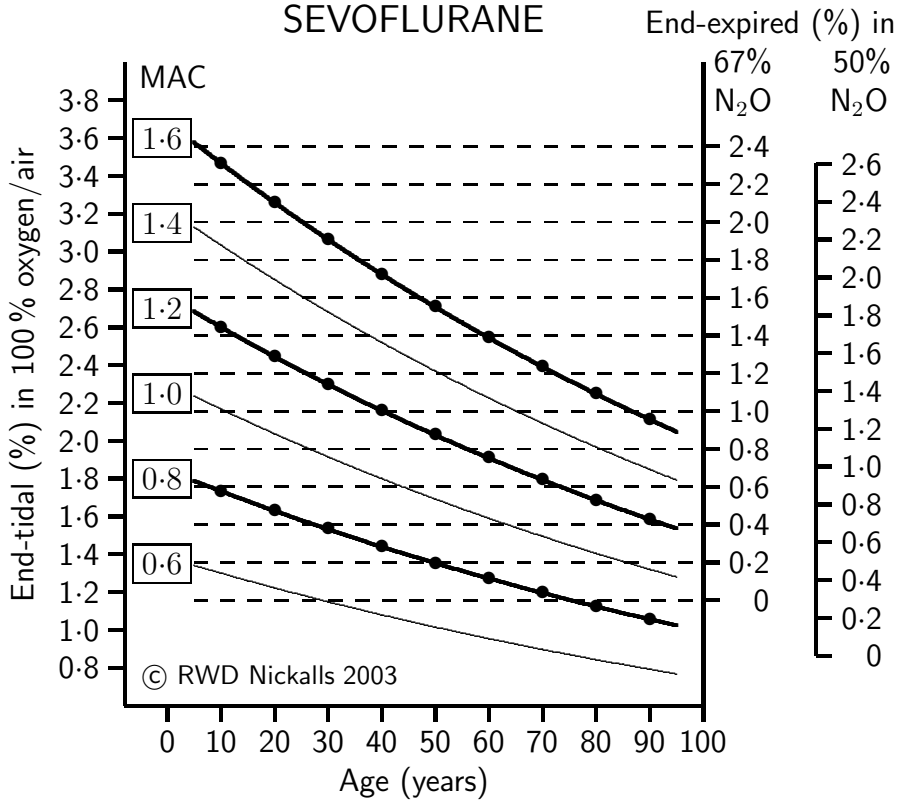
SEVOFLURANE
End-expired (%) in
67% N2O
50% N2O
MAC
1·6
1·4
1·2
1·0
0·8
0·6
End-tidal (%) in 100% oxygen/air
3·8
3·6
3·4
3·2
3·0
2·8
2·6
2·4
2·2
2·0
1·8
1·6
1·4
1·2
1·0
0·8
2·4
2·2
2·0
1·8
1·6
1·4
1·2
1·0
0·8
0·6
0·4
0·2
0
2·6
2·4
2·2
2·0
1·8
1·6
1·4
1·2
1·0
0·8
0·6
0·4
0·2
0
© RWD Nickalls 2003
0 10 20 30 40 50 60 70 80 90 100
Age (years)

Figure 9.2:

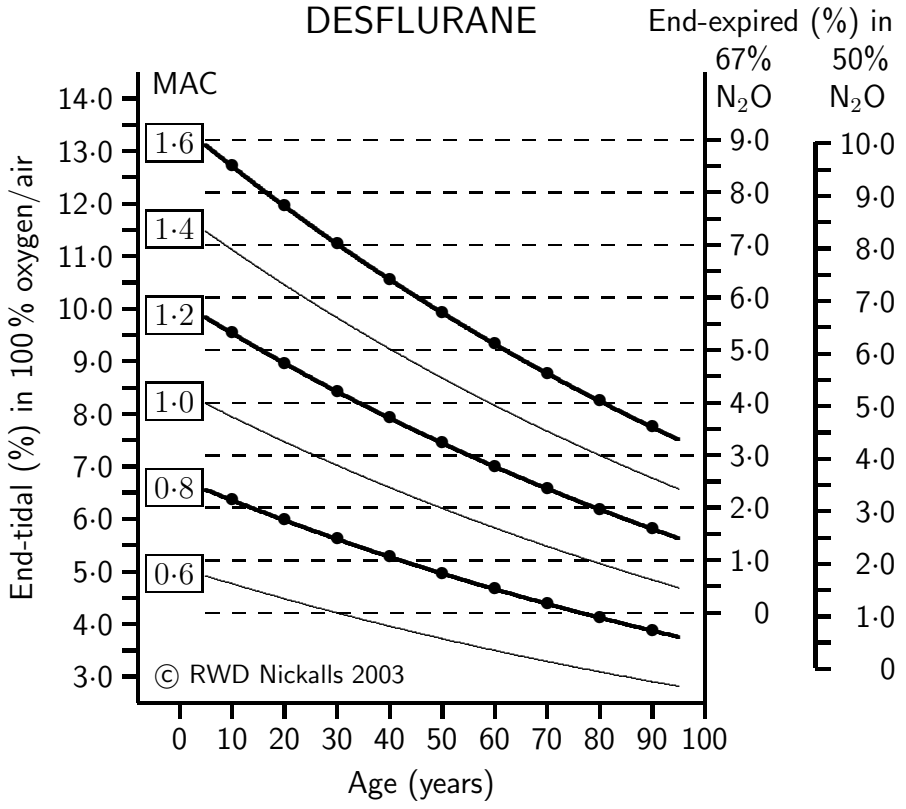
DESFLURANE
End-expired (%) in
67% N2O
50% N2O
MAC
1·6
1·4
1·2
1·0
0·8
0·6
End-tidal (%) in 100 % oxygen/air
14·0
13·0
12·0
11·0
10·0
9·0
8·0
7·0
6·0
5·0
4·0
3·0
9·0
8·0
7·0
6·0
5·0
4·0
3·0
2·0
1·0
0
10·0
9·0
8·0
7·0
6·0
5·0
4·0
3·0
2·0
1·0
0
© RWD Nickalls 2003
0 10 20 30 40 50 60 70 80 90 100
Age (years)

Figure 9.3:

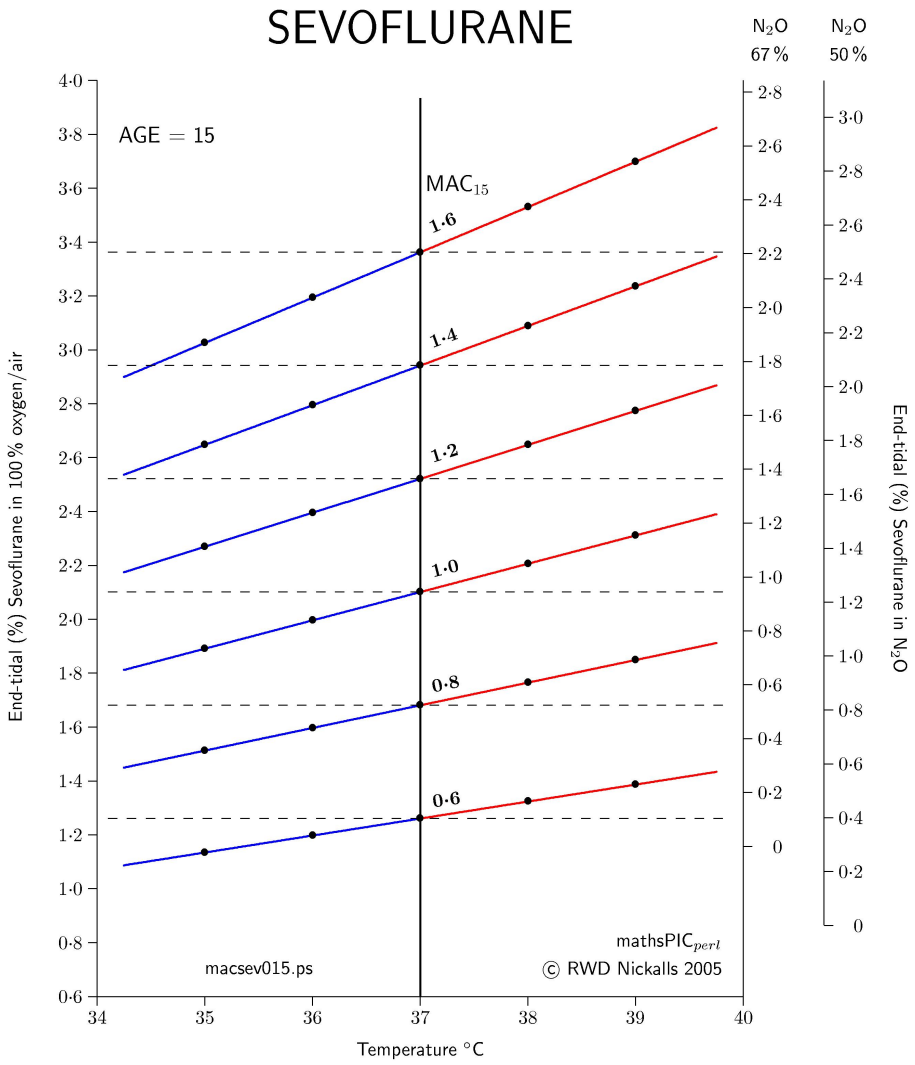

Figure 9.4:
An example of one of the new age and temperature-corrected MAC charts (see Section 9.4.3 for details). A Perl program prompts the user for agent name and patient age and then prints the chart out in the operating theatre. Separate charts for the ages 1–101 yrs are available on the thoracic anaesthesia CD-ROM in both `.pdf` and `.ps` formats for printing out on demand.

9.4.3 Temperature corrected MAC

It is well established that MAC decreases as body temperature decreases. In fact even John Snow was aware of the influence of temperature, as the following extract shows.[28]

> As the narcotism of frogs, by vapour too much diluted to affect animals of warm blood, depends merely on their temperature, it follows that by warming them, they ought to be put into the same condition, in this respect, as the higher classes of animals; and although I have not raised their temperature to the same degree, I have found that as it is increased, they cease to be affected by dilute vapour that would narcotise them at a lower temperature.
>
> Snow (1848a)

However, it is less well known that (a) MAC decreases *linearly* with core temperature fall (approximately 2–5 % reduction in MAC per degree centigrade from 37 °C), and (b) the rate of MAC decrease with temperature fall is considerably more for vapours than for gases; for example the change in MAC / °C for halothane and cyclopropane in dogs is 5·3 % and 2 % respectively (Eger, Saidman, and Brandstater 1965b; Eger 1974). In humans the linear rate of fall of MAC with temperature in the clinical range is approximately 5 % per degree centigrade for isoflurane, sevoflurane and desflurane, while that for nitrous oxide shows essentially no change (Eger 2001).

These findings can be used to combine both age and temperature correction for MAC in a single chart—most easily done by creating a separate chart for each year of age—as shown in Figure 9.4. The additional functionality of such a chart is particularly useful, since the end-tidal agent requirement is most likely to be underestimated in young patients with a pyrexia. In practice, it is a simple matter to create and print this combined age and temperature-corrected iso-MAC chart for a specific patient on demand in the operating theatre.[29]

For example, suppose we wish to deliver 1·2 MAC to a 15 year-old patient with a temperature of 39 °C. The Datex AS/3 and S/5 monitors show a value of 1·2 MAC for an end-tidal sevoflurane concentration (in air) of approximately 2·2 %, whereas the age/temperature correction chart (see Figure 9.4) indicates that to achieve the same MAC value in this patient (age 15 yrs; temp 39 °C) actually requires an end-tidal value of 2·8 % (i.e., a 27 % increase compared with the Datex displayed value).

9.4.4 Dosage and MAC correction

Awareness

The problem of awareness and the need for research in this area is often highlighted (Bergman *et al.* 2002, Guidry 2005, Leslie and Davidson 2010) and, as one might expect, data gathered by automatic anaesthesia management systems (AIMS) has been particularly

[28] This temperature work relates to chloroform—see his Experiment 16 (Snow 1848a).

[29] I have written a Perl program for this which is freely available. This program and separate charts for the ages 0–120 yrs are available on the thoracic CD-ROM in PDF format.

useful in this regard. For example, using archived AIMS data, Driscoll *et al.* (2007) were not only able to establish volatile agent underdosing as the cause of awareness in three cases, but were also able to show that the clinicians' manual component of the relevant parts of the anaesthesia records were unreliable and failed to reflect events accurately.

More recently, the role of underdosing as a cause of awareness during anaesthesia has been highlighted in two large studies (Ghoneim *et al.* 2009, Xu *et al.* 2009), both of which found that awareness was associated with reduced drug dosage, being younger, and with non-volatile anaesthetic techniques. Similarly, Kent (2010) found that the two main causes of awareness in the Closed Claims database were light anaesthesia and anaesthetic delivery problems.

Unfortunately EEG *depth of consciousness* monitoring techniques (e.g., BIS) are still problematic and unreliable (Mychaskiw *et al.* 2001, Rampersad and Mulroy 2005). Furthermore, in spite of several well publicised large neuromonitoring trials and surveys (Ekman *et al.* 2004, Myles *et al.* 2004; Sebel *et al.* 1997; Sebel *et al.* 2004; Avidan *et al.* 2008) there are still no data to suggest, in those cases where volatile agents are used, that neuromonitoring offers any advantage with regard to preventing awareness, over the *rigorous* implementation of 'corrected' MAC monitoring. Indeed, it is significant that the study of 20,000 patients by Sebel *et al.* (2004) actually showed that the BIS-monitored cohort had a *higher* incidence of awareness (0·18%) than the control cohort [30] (0·1%) (McCulloch 2005). In the BIS/MAC study by Avidan *et al.* (2008) the authors concluded that "...Our findings do not support routine BIS monitoring as part of standard practice." Indeed, the associated editorial by Orser (2008) expressed concern regarding BIS-like devices, as follows.

> ... the delegation of critical elements of patient care to a "black box" approach, in which decisive factors are under proprietary control, must be avoided."

Since the MAC paradime has been so successful (White, 2003), and because there are no known *convincingly* documented cases of awareness which are not associated with possible underdosing, it was recently suggested (Nickalls and Mahajan 2010)

> ... that the time has come to reformulate the concept and adopt a new and pragmatic working premis, namely, that *all cases of awareness are due to underdosing unless there is convincing verifiable information to the contrary.* ... We ... must confront the problem of underdosing by putting in place systems which we can have confidence in to deliver an adequate dose, implementing the latest alarms (Umesh 2009), algorithms (Mashour, Esaki Vandervest *et al.* 2009), and corrections for age (Mapleson 1996, Nickalls and Mapleson 2003, Eger 2001), temperature (Eger 2001), and so forth as they come available.

In practice, however, there are studies showing a very low incidence of awareness even without using brain function monitoring (Pollard *et al.* 2007), and when volatile agents are used the end-tidal MAC approach is still the most reliable method for avoiding awareness,

[30] See letter by McCulloch (2005).

and is recommended by the Royal College of Anaesthetists (see RCOA 2006). Indeed, anaesthetists can easily be made even more aware of the current MAC status simply by using use a real-time colour-coded dial-display of corrected MAC (see Figure 9.5).

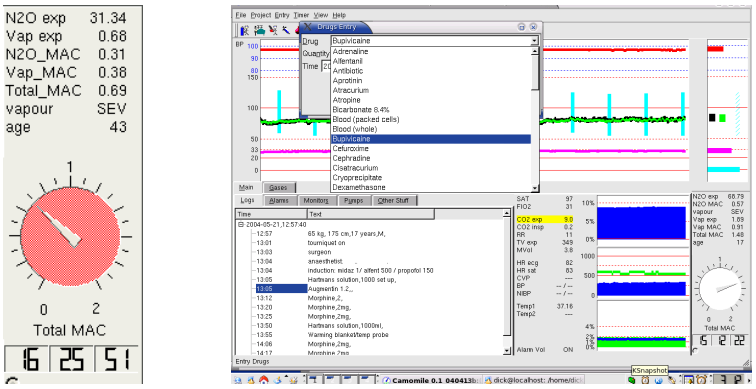

Figure 9.5:

Left: Example of the real-time age-corrected MAC-widget displayed by the author's open-source anaesthesia workstation software [a] interfaced to the Datex S/5 monitor. If the corrected MAC is too low (as shown in this case—total MAC $\approx 0{\cdot}7$) then, in addition to sounding an audible alarm, the dial of the MAC-widget turns red.

Right: Screenshot showing the MAC widget displaying a white dial (corrected MAC in the normal range). The MAC-widget software can easily be run on a laptop interfaced to an anaesthesia monitor.

[a] © Nickalls RWD, Dales S and Nice AK (1996–2011).

What is the minimum MAC multiple which avoids awareness? 1 MAC has long been regarded as a significant boundary since isoflurane at 1 MAC was shown to prevent implicit memory during surgery (Dwyer *et al.* 1992). More recently this problem was addressed by Hardman and Aitkenhead (2005), who stated that a stable end-tidal value greater than 1 MAC makes awareness extremely unlikely, as follows.

> Risk of awareness correlates with depth of anaesthesia. ... Fortunately, clinical investigations have shown a reasonably reliable association between recall and MAC; patients exhaling more than 0·8 MAC are unlikely to recall intraoperative events, and spontaneous recall is virtually eliminated if $>$ 1 MAC is exhaled, except after a sudden increase in inspired concentration.
>
> Hardman and Aitkenhead (2005)

That the end-tidal agent concentration should be maintained $\geq 1\ \text{MAC}_{age}$ in order to reliably avoid awareness is consistent with a recent fMRI finding by Kerssens *et al.* (2005), namely that while auditory activation in a group of 6 subjects (mean age 23 years) was detected

when breathing 1% end-tidal sevoflurane in oxygen/air (0·5 MAC_{age}), such activation was absent when breathing 2% end-tidal sevoflurane (i.e., when breathing 1 MAC, since $MAC_{23}^{sevo} = 2\%$).

It is significant, therefore, that in the BIS/MAC study by Avidan *et al.* (2008) the end-tidal agent concentration was less than 0·7 MAC in three of the four cases of definite awareness, and in seven of of the nine cases of possible awareness. Thus the lower acceptable limit of 0·5 MAC suggested by Eger and Sonner (2005), Myles (2007) would seem to be far too low to reliably prevent awareness. Consequently the values suggested by Hardman and Aitkenhead (2005)—see above—particularly when age and temperature corrected, would seem to be the best current advice.

Note that the MAC value displayed by monitors having no age or temperature correction is most likely to underestimate the true MAC requirement in young patients with a high temperature (Section 9.4.3) and (possibly) with red hair (Liem *et al.* 2004). Indeed, it may be significant, therefore, that the two patients with documented awareness during BIS monitoring with sevoflurane reported by Ekman *et al.* (2004) were quite young (aged 16 and 22 years). Unfortunately the details of the aware patients who received volatile agents in the non-BIS group were not given.

Research

In all work relating to depth of anaesthesia or awareness, it is essential to collect accurate real-time end-tidal anaesthetic gas (ETAG) concentrations and core temperatures using automated anaesthesia record keeping (AARK) equipment, drugs and doses used, as well as patient age, height, gender and hair-colour. The presented awareness-related data must be sufficient to enable readers to calculate the corrected MAC for *each patient*; consequently the observed ETAG concentrations for each patient should always be presented. Where MAC corrections have been applied, the literature source of the corrections used must be indicated. Furthermore, mean age-corrected values need to be correctly determined; for example, the age correction for MAC is non-linear and hence the mean MAC value for a group must be derived from the corrected MAC of each individual subject/patient.

In view of the importance of determining minimum MAC values for reliably preventing awareness, journal editors should ensure that awareness-related MAC data presented in journal articles are sufficient to allow readers to determine the corrected MAC values for each patient (Nickalls and Mahajan 2010).

Data sharing

Ideally all cases of inadvertent awareness should be documented, and archived, together with all the anaesthesia data associated with such cases (including all machine-automated end-tidal data) and placed in the public domain. Such a database could then form the basis of research, and may therefore, help "... recognise those few cases which may suggest either that the accepted dosage threshold should be raised or, perhaps, a significant pharmacogenetic difference" (Nickalls and Mahajan 2010).

However, although original data documented in journals is still often difficult to access from the authors or organisation (Wicherts *et al.* 2006, Anon 2006, Kaiser 2008), fortunately the climate of opinion is now strongly in favour of data-sharing, with funding organisations increasingly stipulating that authors place their data in open-access repositories within a set period after publication in peer-reviewed journals (Short 2007, Wadman 2009). Nevertheless, we should continue to press for even more safeguards; for example, the adoption by anesthesia journals of an authorship policy specifying the preservation and sharing of original data (Anon 2009a). Authors and researchers must embrace the new culture of '*integrity, access and stewardship*' (Anon 2009b)—not only making the data available, but safe-guarding it as well.

9.4.5 References

- Allman KG and Wilson IH (Eds.) (2006). *Oxford Handbook of Anaesthesia.* 2nd. ed., 1160–1162.
- Anon [editorial] (2006). A fair share. *Nature*; 444, 653–654 (7th December).
- Anon [editorial] (2009a). Authorship policies. *Nature*; 458, 1078 (30th April).
- Anon [editorial] (2009b). Information overload. *Nature*; 460, 551 (30th July).
- Avidan MS, Zhang L, Burnside BA *et al.* (2008). Anesthesia awareness and the bispectral index. *New Engl. J. Med.*; 358, 1097–1108. [see also the accompanying editorial by Orser (2008)]
- Bergman IJ, Kluger MT and Short TG (2002). Awareness during general anaesthesia: a review of 81 cases from the Anaesthetic Incident Monitoring Study. *Anaesthesia*; 57, 549–556.
- Borzova VV and Smith CE (2010). Monitoring and Prevention of Awareness in Trauma Anesthesia. *The Internet Journal of Anesthesiology* [ISSN: 1092-406X], 23, No 2. (http://www.ispub.com/journal/the_internet_journal_of_anesthesiology/)
- Bowdle TA, Sebel PS, Ghoneim MM *et al.* (2005). How likely is awareness during anesthesia? *Anesthesia and Analgesia*; 100, 1545. [reply to letter by Eger EI and Sonner JM (2005)]
- Driscoll WD, Columbia MA and Peterfreund RA (2007). Awareness during general anaesthesia: analysis of contributing causes aided by automatic data capture. *Journal of Neurosurgical Anesthesiology*; 19, 268–272.
- Dwyer R, Bennett HL, Eger EI and Peterson N (1992). Isoflurane anesthesia prevents unconscious learning. *Anesthesia and Analgesia*; 75, 107-112.

- Eger EI (1974). Anesthetic uptake and action. (Williams and Wilkins Company, Baltimore, USA), p. 12.
- Eger EI (2001). Age, minimum alveolar anesthetic concentration, and minimum alveolar anesthetic concentration-awake. *Anesthesia and Analgesia*; 93, 947–953. [has an appendix on temperature correction]
- Eger EI (2002). A brief history of the origin of Minimum Alveolar Concentration (MAC). *Anesthesiology*; 96, 238–239.
- Eger EI II, Brandstater B, Saidman IJ, Regan M, Severinghaus J and Munson E (1965). Equipotent alveolar concentrations of methoxyflurane, halothane, diethyl ether, fluroxene, cyclopropane, xenon and nitrous oxide in the dog. *Anesthesiology*; 26, 771–777.
- Eger EI, Eisenkraft JB and Weiskopf RB (2003). The pharmacology of inhaled anesthetics. 327 pp. (Sponsored by the Dannemiller Memorial Education Foundation, and also Baxter Healthcare Corporation) [Library of Congress no. TXV1-035635]
- Eger EI II, Saidman IJ and Brandstater B (1965a). Minimum alveolar anesthetic concentration: A standard of anesthetic potency. *Anesthesiology*; 26, 756–763.
- Eger EI II, Saidman IJ and Brandstater B (1965b). Temperature dependence of halothane and cyclopropane anesthesia in dogs: Correlation with some theories of anesthetic action. *Anesthesiology*; 26, 764–770. [from Eger 1974]
- Eger EI and Sonner JM (2005). How likely is awareness during anesthesia? *Anesthesia and Analgesia*; 100, 1544. [see reply by Bowdle *et al.* (2005)]
- Eisele JH and Eger EI (1967). Narcotic properties of carbon dioxide in the dog. *Anesthesiology*; 28, 856–865. [cited from *Anaesthesia and Analgesia* (2001); 93, 398]
- Ekman A, Lindholm M-L, Lennmarken C and Sandin R (2004). Reduction in the incidence of awareness using BIS monitoring. *Acta Anaesthesiol. Scand.*; 48, 20–26.
- Ghoneim MM, Block RI (1997) Learning and memory during general anesthesia. An update. *Anesthesiology*; 87, 387-410
- Ghoneim MM, Block RI, Haffarnan M and Mathews M (2009). Awareness during anesthesia: risk factors, causes and sequelae: a review of reported cases in the literature. *Anesthesia and Analgesia*; 108, 527–535.
- Gregory GA, Eger EI and Munson ES (1969). The relationship between age and halothane requirement in man. *Anesthesiology*; 30, 488–491. [from Eger 1974]
- Guidry OF (2005). Awareness monitoring: some personal opinions. *ASA Newsletter*; 69 (January). http://www.asahq.org/Newsletters/2005/

- Hardman JG and Aitkenhead AR (2005). Awareness during anaesthesia. *Continuing Education in Anaesthesia, Critical Care & Pain*; 5, 183–186.
- Kaiser J (2008). Making clinical data widely available. *Science*; 322, 217–218 (October 10).
- Katoh T, Bito H and Sato S (2000). Influence of age on hypnotic requirement, Bispectral Index, and 95 % spectral edge frequency associated with sedation induced by sevoflurane. *Anesthesiology*; 92, 55–61.
- Kent CD (2010). Awareness during general anesthesia: ASA Closed Claims Database and Anesthesia Awareness Registry. *ASA Newsletter*; 74 (February), 14–16. http://www.asahq.org/Newsletters/2010/
- Kerssens C, Hamann S, Peltier S, Hu XP, Byas-Smith MG and Sebel PS (2005). Attenuated brain response to auditory word stimulation with sevoflurane. A functional magnetic imaging study in humans. *Anesthesiology*; 103, 11–19.
- Kofke WA (2003). An interview with John W. Severinghaus. *Association of University Anesthesiologists (AUA) Update*; Fall 2003 issue. http://www.auahq.org/fall03aua.pdf
- Lerou JGC (2004). Nomogram to estimate age-related MAC. *Br. J. Anaesth.*; 93, 288–291.
- Leslie K and Davidson (2010). Awareness during anesthesia: a problem without solutions? *Minerva Anestesiologica*; 76, 624-628.
- Liem EB, Lin C-M, Suleman M, Doufas AG, Gregg RG, Veauthier JM, Loyd G and Sessler DI (2004). Anesthetic requirement is increased in redheads. *Anesthesiology*, 101, 279–83. [MAC requirement is increased by 19 %]
- MacQuitty B (1969). *The battle for oblivion.* (GG Harrap & Co Ltd., London.)
- Maltby RJ (Ed.) (2002). *Notable names in anaesthesia.* (Royal Society of Medicine Press, London). [ISBN: 1853-155-128]. [includes EI Eger, WW Mapleson, J Severinghaus, J Snow]
- Mapleson WW (1979). From Clover to computer: towards programmed anaesthesia? *Anaesthesia*; 34: 163–172. [an edited version of the 19th Joseph Clover Lecture]
- Mapleson WW (1996). Effect of age on MAC in humans: a meta-analysis *Br. J. Anaesth.*; 76: 179–185. http://bja.oupjournals.org/cgi/reprint/76/2/179.pdf
- Mashour GA, Esaki RK, Vandervest JC, Shanks A and Kheterpal S (2009). A novel electronic algorithm for detecting potentially insufficient anesthesia: implications for the prevention of intraoperative awareness. *J. Clin. Monit. Comput.*; 23, 273–277.

- McCulloch TJ (2005). Use of BIS monitoring was not associated with a reduced incidence of awareness. *Anesthesia and Analgesia*; 100, 1221–1222. [comments on the Sebel *et al.* 2004 paper]

- Merkel G and Eger EI (1963). A comparative study of halothane and halopropane anesthesia: Including a method for determining equipotency. *Anesthesiology*; 24, 346–57.

- Mychaskiw G, Horowitz M, Sachdev V and Heath BJ (2001). Explicit intraoperative recall at bispectral index of 47. *Anesth. Analg.*; 92, 808–809.
[28 yr male with awareness during the sternal split for a CABG. Values at this stage were $F_{I_{O_2}}$ 0·26, $F_{I_{N_2O}}$ 0·67, *inspired* sevoflurane 2%]

- Myles PS (2007). Prevention of awareness during anaesthesia. *Best Practice and Research in Clinical Anaesthesiology*; 21, 345–355.

- Myles PS, Leslie K, McNeil J, Forbes A and Chan MT (2004). Bispectral index monitoring to prevent awareness during anaesthesia: the B-Aware randomised controlled trial. *Lancet*; 363, 1757–1763.

- Nickalls RWD and Mapleson WW (2003). Age-related iso-MAC charts for isoflurane, sevoflurane and desflurane in man. *Br. J. Anaesth.*; 91, 170–174.
http://www.doi.dx/10.1093/bja/aeg132

- Nickalls RWD and Mahajan RP (2010). Awareness and anaesthesia: think dose, think data. *Br. J. Anaesth.*; 104, 1–2. [Editorial]
http://www.doi.dx/10.1093/bja/aep360

- Orser BA (2008). Depth-of-anesthesia monitor and the frequency of intraoperative awareness. *New Engl. J. Med.*; 358, 1189–1191. [editorial to the Avidan *et al.* 2008 study]

- Peyton PJ, Chong M, Stuart-Andrews C, Robinson GJB, Pierce R and Thompson BR (2007). Measurement of anaesthetics in blood using a conventional infrared clinical gas analyzer. *Anesthesia and Analgesia*; 105, 680–687. [accuracy and precision of the Datex Capnomac compares well with gas chromatography methods]

- Pollard RJ, Coyle JP, Gilbert RL and Beck JE (2007). Intraoperative awareness in a regional medical system. *Anesthesiology*, 106, 269–274.

- Rampersad SE and Mulroy MF (2005). A case of awareness despite an 'adequate depth of anesthesia' as indicated by a bispectral index monitor. *Anesth. Analg.*; 100, 1363–1364.

- RCOA (2006). *Loss of consciousness monitoring*. A statement by the Royal College of Anaesthetists and the Association of Anaesthetists of Great Britain and

Ireland. Available from: http://www.anaesthesiauk.com/article.aspx?articleid=100622

- Sandin RH, Enlund G, Samuelsson P and Lenmarken C (2000). Awareness during anaesthesia: a prospective case study. *Lancet*; 355, 707–711.
- Sebel PS, Lang E, Rampi IL *et al.* (1997). A multicenter study of bispectral electroencephalogram analysis for monitoring anaesthetic effect. *Anaesthesia and Analgesia*; 84, 891–899.
- Sebel PS, Bowdle TA, Ghoneim MM *et al.* (2004). The incidence of awareness during anesthesia: a multicenter United States study. *Anesthesia and Analgesia*; 99, 833–839.
- Severinghaus JW (2009). Gadgeteering for health care: [The JW Severinghaus lecture on translational science] *Anesthesiology*; 110, 721–728.
- Short R (2007). Open access will mean peer review becomes "*the job of the many, not the select few*". *British Medical Journal*; 334 (17 February), 330.
- Snow J (1847). *On the inhalation of the vapour of ether in surgical operations.* Reprinted in *Br. J. Anaesth.* (1953); 25, pp. 53–67 (part 1), 162–169 (part 2), 253–262 (part 3), 349–382 (part 4). Also available from UCLA Department of Epidemiology website: http://www.ph.ucla.edu/epi/snow.html
- Snow J (1848a). On narcotism by the inhalation of vapours (Part I). *London Medical Gazette*; 6NS [31], 850–854 [included in Snow 1848b]
- Snow J (1848b). On narcotism by the inhalation of vapours (parts I–VII). (Wilson and Ogilvy, London). A facsimile edition with an introductory essay by RH Ellis (Royal Society of Medicine Services Ltd., London, 1991) ISBN 1-85315-158-0
- Soto R, Nguyen TC and Smith RA (2005). A comparison of Bispectral Index and Entropy, or how to misinterpret both. *Anesthesia and Analgesia*; 100, 1059–1061.
- Stone ME, Meyer MR and Alston TA (2010). Elton Romeo Smilie, the not-quite discoverer of ether anesthesia. *Anesthesia & Analgesia*; 110, 195–197.
- Umesh G, Jasvinder K and Shetty N (2009). Low minimum alveolar concentration alarms: a standard for preventing awareness during general anaesthesia. *J. Clin. Monit. Comput.*; 23, 185–186.
- Vinten-Johansen P, Brody H, Paneth N, Rachman S and Rip M (2003). Cholera, chloroform and the science of medicine: a life of John Snow. (Oxford University Press, UK)

[31] 6NS indicates New Series No 6.

- Wadman M (2009). Open-access policy flourishes at NIH. *Nature*; 458, 690–691 (9th April).
- White D (2003). Uses of MAC. *Br. J. Anaesth.*; 91, 167–169. [editorial]
- Wicherts JM, Borsboom D, Kats J and Molenaar D (2006). The poor availability of psychological research data for reanalysis. *American Psychologist*; 61, 726–728. [cited in Anon 2006]
- Xu L, Wu AS, Yue Y (2009). The incidence of intra-operative awareness during general anesthesia in China: a multicenter observational study. *Acta Anaesthesiologica Scandinavica*; 53, 873–882.

9.5 Arterial line

9.5.1 History

The first direct measurement of arterial blood pressure is generally said to have been in 1733 by Stephen Hales (1677–1761) using a glass tube 9 feet long connected flexibly (using the trachea of a goose) to the femoral and carotid arteries of horses (Comroe 1977, pp. 15–17). Some eight years earlier the physician and mathematician Daniel Bernoulli (1700–1782) was measuring fluid pressure in pipes using a narrow tube (Quinney 1997). In 1828 Jean-Louis Poiseuille (1799–1869) developed this technique further (see also: Zuck 1997) using a U-tube filled with mercury to determine the pressure at various points along the aorta (his later researches into flow in small tubes led to his famous Poiseuille's Law).

The first clinically useful placement of an arterial catheter for this purpose was developed by Peterson *et al.* (1949). They described their method as follows.

> A small plastic catheter, inserted into an artery through a needle, is left in the artery when the needle is withdrawn. Attached to a capacitance manometer, this technique permits recording for long periods of time without discomfort and allows relatively free mobility of the subject.
>
> Comroe (1977), p. 36

Use of the strain-gauge (Tomlinson, 1876) for transducing arterial pressure was first described a few years earlier by Lambert and Wood (1947). See letter by Kannan (2005) for recent use of ultrasound to facilitate arterial line placement.

- Barr PO (1961). Percutaneous puncture of the radial artery with a multipurpose Teflon cannula for indwelling use. *Acta Physiol. Scand*; 51, 643.
- Comroe JH (1977). Retrospectroscope: insights into medical discovery. (Von Gehr Press, Menlo Park, California, USA).

- El-Hamamsy I, Düurrleman N, Stevens L-M, Leung TK, Theoret S, Carrier M and Perrault LP (2003). Incidence and outcome of radial artery infections following cardiac surgery. *Annals of Thoracic Surgery*; 76, 801–804. [strict systematic changing of arterial lines on a timely basis is unwarranted]
- Hales S (1733). *Statical essays: Containing haemastatics.* vol 2. (Innys and Manby, London). 361 pp.
- Kannan S (2005). Another use for ultrasound in the ICU. *Anaesthesia*; 60, 944. [used a 7 MHz ultrasound probe; useful in oedematous patients; 7 refs]
- Peterson LH, Dripps RD and Risman G (1949). A method for recording the arterial pressure pulse and blood pressure in man. *Am. Heart J.*; 37, 771–782.
- Poiseuille JLM (1828). *Recherches sur la Force du Coeur Aortique*; Thèse No. 166 (Didot, Paris).
- Quinney DA (1997). Daniel Bernoulli and the making of the fluid equation. http://plus.maths.org.uk/issue1/bern/index.html
- Tomlinson H (1876). On the increase in resistance to the passage of an electric current produced on wires by stretching. *Proc. Soc. Exp. Biol. Med.*; 64, 186–190.
- Wong AYC and O'Regan AM (2003). Gangrene of digits associated with radial artery cannulation. *Anaesthesia*; 58, 1034–1035. [overview of rare complications, and discusses use of the 'modified' Allen test]
- Zuck D (1997). Anaesthesia and physiology: the first twenty years. *The History of Anaesthesia Society Proceedings*; 20, 75–90.

9.5.2 Anatomy

An extensive collateral network of superficial and deep palmar arches normally connects the radial and ulna arteries in the hand. However, in 58 % of patients the palmar arches are incomplete, and of these 'incomplete' cases approximately 4 % will suffer significant vascular insufficiency if the radial artery is removed or occluded (Cable, Mullany & Schaff 1999; Lippert H and Pabst R 1985) — see Allen test below.

- Brzezinski M, Luisetti T and London MJ (2009). Radial Artery Cannulation: A Comprehensive Review of Recent Anatomic and Physiologic Investigations. *Anesthesia and Analgesia*, 109, 1763–1781.
- Coleman SS and Anson BJ (1961). Arterial patterns in the hand based upon a study of 650 specimens. *Surg. Gynecol. Obstet.*; 113, 409.
- Husum B and Palm T (1978). Arterial dominance in the hand. *Br. J. Anaesth.*; 50, 913.

- Lippert H and Pabst R (1985). *Arterial variations in man: classification and frequency.* (JF Bergmann Verlag, Munich, Germany). [cited by Cable, Mullany & Schaff 1999]
- Riekkinen HV, Karkola KO and Kankainen A (2003). The radial artery is larger than the ulna. *Annals of Thoracic Surgery*, 75, 882–884. [mean internal diameter is 3·1 mm (range: 2–4 mm)]

9.5.3 Allen test

Edgar V Allen (1900–1961) was a physician at the Mayo Clinic, and co-author of a textbook on vascular medicine (Allen, Barker and Hines 1946). He described a simple test (the so-called Allen test) to reveal ulnar or radial artery occlusion at the wrist (Allen 1929). His description with respect to the ulnar artery is as follows.

> If obstruction of the ulnar artery is suspected, the radial arteries are located by their pulsations; the examiner places one thumb lightly over each radial, with the four fingers of each hand behind the patient's wrist, thus holding the wrist lightly between the thumb and fingers. The patient closes his hands as tightly as possible for a period of 1 minute in order to squeeze the blood out of the hand; the examiner compresses each wrist between the thumb and fingers, thus occluding the radial arteries; the patient quickly extends his fingers partially while compression of the radial arteries is maintained by the examiner. The return of color to the hand and fingers is noted. In individuals with an intact arterial tree the pallor is quickly replaced by rubor of a degree higher than normal.
>
> Cable, Mullany & Schaff (1999)

Before 'harvesting'[32] or even cannulating the radial or ulnar artery, the adequacy of collateral vessels should be assessed by an Allen test (after EV Allen 1929), to determine if they alone can adequately supply the hand. If a vessel fails the Allen test, then the other vessel certainly should not be harvested, and probably ought not to be cannulated either.

Modified Allen test

Erroneous results can arise if the test is not performed correctly (Greenhow 1972). Note that the wrist must not be hyperextended as this can cause vessel occlusion and invalidate the test (Fuhrman *et al.* 1992). The slightly more controlled so-called 'modified' Allen test (Vaghadia *et al.* 1988) is now generally used (compressing both arteries simultaneously), in conjunction with the following 'pass' or 'fail' times.

> [both] the ulnar and radial arteries are compressed at the wrist for $\geq$ 30 secs to induce hand ischaemia, while the hand is drained of blood by tight clenching. The test vessel is then released and the time to adequate perfusion of the tips of the fingers and thumb

[32] The radial artery is sometimes removed (known as 'harvesting') for use in coronary-artery or temporal-artery bypass procedures—see Royse *et al.* (1999).

> noted. The vessel is said to pass or fail the test as follows: pass (< 5 secs); equivocal (6–10 secs); fail (> 10 secs)
>
> Royse *et al.* (1999)

Note that the vessels should actually be compressed just proximal to the point where the tip of the cannula is expected to lie, in order to detect essential collateral branches *distal* to the likely cannula tip position (Gandhi and Reynolds 1983). Plethysmography is more sensitive than either the Allen test or pulse-oximetry (Fuhrman *et al.* 1992).

- Allen, EV (1929). Thrombo-angiitis obliterans:[33] methods of diagnosis of chronic occlusive arterial lesions distal to the wrist, with illustrative cases. *American Journal of Medical Sciences*; 178 (August), 237–244.
- Allen, EV, Barker NW and Hines EA (1946). *Peripheral vascular diseases.* (WB Saunders Company, Philadelphia, USA). [from Wright 1952]
- Cable DG, Mullany CJ and Schaff HV (1999). The Allen test. *Annals of Thoracic Surgery*; 67, 876–877. [excellent – includes a photograph of Allen]
- Fuhrman TM, Pippin WD, Talmage LA and Reilley TE (1992). Evaluation of collateral circulation of the hand. *J. Clinical Monitoring and Computing*; 8, 28–32.
- Gandhi SK and Reynolds AC (1983). A modification of Allen's test to detect aberrant ulna collateral circulation. *Anesthesiology*; 59, 147–148.
- Glavin RJ and Jones HM (1989). Assessing collateral circulation in the hand — four methods compared. *Anaesthesia*; 44, 594–595.
- Greenhow DE (1972). Incorrect performance of Allen's test—ulnar-artery flow erroneously presumed inadequate. *Anesthesiology*; 37, 356–357.
- Paul BZS and Feeney CM (2003). Combining the modified Allen's test and pulse oximetry for evaluating ulna collateral circulation to the hand for radial artery catheterization of the ED [34] patient. *The California Journal of Emergency Medicine*; 4, 89–91.
- Royse *et al.* (1999). Radial artery harvest technique, use and functional outcome. *European J. of Cardio-thoracic Surgery*; 15, 186–193. [available for download at: http://www.heartweb.com.au/PDFs/RAharvest.pdf]
- Sinton I (2003). Digital ischaemia after ulnar artery cannulation. *Br. J. Anaesth.*; 91, 302–303. [letter]
- Vaghadia H, Schechter MT, Sheps SB and Jenkins LC (1988). Evaluation of a postocclusive reactive circulatory hyperaemia (PORCH) test for the assessment of ulna collateral circulation. *Can. J. Anaesth.*; 35, 591–8. [a 'modified' Allen test]

[33] Buerger's disease.
[34] Emergency Department

9.5.4 Systolic pressure variation

Real-time measurement of systolic-diastolic pressure variation with respect to spontaneous ventilation or with IPPV may be useful as an index of hypovolaemia, either via pulse oximetry waveform variation or via direct arterial measurement.

- Fujita Y and Sari A (2003). On-line monitoring of systolic pressure variation. *Anesthesia and Analgesia*; 96, 1529-1530.
- Reuter DA, Felbinger TW, Kilger E *et al.* (2002). Optimizing fluid therapy in mechanically ventilated patients after cardiac surgery by an on0line monitoring of left ventricular stroke volume variations: comparison with aortic systolic pressure variations. *Br. J. Anaesth.*; 88, 124–126.

9.5.5 Complications

Complications from arterial cannulation are rare, but therapeutic vasodilation in the form of stellate ganglion block (Gyanendra *et al.* 1998), or use of intra-arterial phentolamine (Burrell 1977) or papaverine is sometimes required.

- Burrell AR (1977). Treatment of ischaemia following radial artery cannulation. *Anaesthesia and Intensive Care*; 5, 388. [used intra-arterial phentolamine (diluted to 0·5 mg/ml) and gave a 3 ml bolus, followed a while later by a 5 ml bolus.].
- Gyanendra U and Kashyap L (1998). Accidental single brachial artery puncture leading to reversible ischaemia of the upper limb. *Intensive Care Medicine*; 24, 197. [severe spasm following 16-G needle puncture treated using repeated stellate ganglion block]
- Leroy O, Billiau V, Beuscart C, Santre C, Chidiac C, Ramage C and Mouton Y (1989). Nosocomial infections associated with long-term radial artery cannulation. *Intensive Care Med.*; 15, 241–246.
- Lindsay SL, Kerridge R and Collett BJ (1987). Abscess following cannulation of the radial artery. *Anaesthesia*; 42, 654–657.
- Mastan M and Van Oldenbeek C (2003). Digital ischaemia after ulnar artery cannulation. *Br. J. Anaesth.*; 90, 111. [letter]. [see reply: Sinton I (2003); 91, 302–303; uses a modified Allen test]
- Ryan DW (1989). Limitations of invasive intravascular monitoring. *Intensive Therapy and Clinical Monitoring*; 10, 216–220.
- Slogoff S, Keats AS and Arlund C (1983). On the safety of radial artery cannulation. *Anesthesiology*; 59, 42–47.
- Wilkins RG (1985). Radial artery cannulation and ischaemic damage—a review. *Anaesthesia*; 40, 896–899.

9.6 Central venous catheter

9.6.1 History

The development of intravascular catheters and the techniques for inserting them has resulted in important advances both diagnostically (angiography) and therapeutically (CVP & Hickman lines; angioplasty).

Werner Forssmann

In the 1920s Werner Forssmann (1904–1979), then a surgical resident, was looking for safer ways of delivering cardio-active drugs to the heart (i.e., other than via direct needle injection), and eventually he hit upon the idea of using a long IV catheter. In 1929, when he was only 26, Forssmann tested this idea in a Berlin hospital, by inserting a long urinary catheter via the antecubital fossa into his own right atrium and confirmed its intra-cardiac position radiologically. He went on to use this method for injecting intra-cardiac contrast in animals, paving the way for diagnostic cardiac angiography, for which he was awarded the Nobel Prize in 1956, together with Cournand (1895–1988) & Richards (1895–1973). The following translation of part of Fossmann's original article (Forssmann, 1929) is by Luft (1994).

> In cases of shock, such as those engendered by sudden cardiac standstill, or during anesthetic emergencies and poisonings, it may be desirable to deliver medications directly to the heart itself. ... Nevertheless intracardiac puncture is a dangerous procedure for several reasons, including injury to the coronary arteries and its branches, pericardial tamponade, injury to the diaphragm, and pneumothorax. ... For these reasons I considered a new method to approach the heart in a less dangerous fashion, namely the catheterisation of the right heart from the venous system.
>
> Experiments on a cadaver were productive. I was able to catheterize any vein in the antecubital fossa and was able to regularly reach the right ventricle. ... I next undertook experiments on a living subject, namely on myself. I first convinced a colleague to puncture a vein in my right antecubital fossa with a large needle. I next advanced a well-oiled ureteral catheter size 4 Charriere in diameter through the needle into the vein. The catheter allowed itself to be advanced with trivial ease to 35 cm. Because my friend objected to our proceeding with these experiments further, we broke them off even though I felt perfectly well. One week later I tried again alone. I anesthetized my own left antecubital fossa and because I was not able to manipulate the needle by myself I constructed a "cut-down" and advanced the catheter along its full 65 cm length. From surface estimates, I reasoned that the catheter tip would be at the level of the heart.
>
> I documented the position of the catheter with roentgenograms that I obtained by standing in front of the fluoroscope while observing the catheter in a mirror held by a nurse. In conclusion, I would like to point out the utility of this technique in providing new opportunities to research the metabolic activities and actions of the heart.
>
> Forssemann (1929) [*From*: Luft (1994)]

André Cournand and Dickinson Richards

Cournand and Richards extended Forssmann's intravascular catheter concept and developed long single and double-lumen catheters which allowed them to sample blood and pressures from the right heart and pulmonary artery (c. 1940s). They also determined approximate left atrial pressures by wedging the catheters by pushing them as far as they would go (i.e., not balloon-occlusion wedge pressures as determined by Swan and Ganz in 1967). They studied cardio-pulmonary physiology and patho-physiology, and showed that hypoxia, sufficient to make the arterial oxygen saturation less than 80 %, resulted in significant pulmonary vasoconstriction and a rise in pulmonary artery pressure (Cournand 1956; Richards 1956). Interestingly, they also showed that an infusion of acetylcholine (0·5 mg/min) into the pulmonary artery reversed the pulmonary vasoconstriction while not affecting the systemic blood pressure (Harris *et al.* 1956; Cournand 1956).

Sven-Ivar Seldinger

Radiologists often need to insert long large-diameter catheters into arteries in order to inject contrast into distant vessels. In the early 1950s, however, the two existing techniques had significant shortcomings. For example, the catheter-through-needle technique was associated with a significant leak at the vessel entry point (catheter smaller than needle), and the long narrow catheters made it difficult to inject contrast fast enough to be effective. The catheter-over-needle technique was only feasible with quite short catheters (since the needle did not bend, and long needles were difficult to manipulate safely).

In 1952 Sven-Ivar Seldinger (1921–1998) a Swedish radiologist at the Karolinska Hospital, Stockholm overcame these difficulties by developing his catheter-over-guidewire technique (Seldinger 1953; Seldinger 1987; Higgs *et al.* 2005; Greitz 1999). He actually used a guidewire with a straight flexible tip. Seldinger described the process of development as follows.

> However, rightly or not, some people considered the procedure [translumbar aortography] hazardous and searched for a technique where a catheter could be inserted via a peripheral artery. Surgical cut down methods had been reported ... and Bierman *et al.* (1951) ... suggested a percutaneous technique in which a catheter was inserted through a puncture instrument into the femoral artery and advanced to the aorta. The catheter had to be wide enough to permit a very rapid injection. If not, the contrast medium would be so diluted by the voluminous aortic bloodflow that diagnostic angiographs would not be obtained. In turn a very wide-bore puncture instrument, with consequent risk of trauma, was required.
>
> Thus there was obviously a need for an improved percutaneous method for aortography, and one of the requirements to the solution was an increased bore of the catheter. ... There existed a "puncture equipment" named after Cournand, consisting of an inner sharp needle in an outer blunt cannula, the edge exceeding the cannula by one or two mm. One alternative was to use a flexible catheter instead of the cannula, but it would certainly be tricky to handle an inner needle, half a meter or more long. I avoided this

> trouble by cutting a side hole on a polythene catheter at such a level that a cutting needle of convenient length, when inserted through it, exceeded the tip of the catheter by one or two mm. After some moulding of the catheter and a minute incision in the skin, this instrument could be inserted into the artery by percutaneous puncture.
>
> Some obvious disadvantages were inherent in this technique. For instance, the thin-walled catheters were so flexible that, sometimes it was impossible to advance them further into the vessel. This difficulty could often be overcome. When intravascular position was obtained, the needle could be withdrawn from the side hole and replaced by a semi-flexible metal wire which was introduced through the entire length of the catheter to support it.
>
> Now! After an unsuccessful attempt to use this technique I found myself, disappointed and sad, with three objects in my hand—a needle, a wire and a catheter—and, in a split second, I realised in what sequence I should use them: *needle in—wire in—needle off—catheter on wire—catheter in—catheter advance—wire off.*
>
> I have been asked how this idea turned up and I can quote Phokion,[35] the Greek: "I had a severe attack of common sense."
>
> The tools could not be less complicated; they could be found among the instruments of any hospital and, if necessary, could be completed at the nearest ironmonger's. Any handy person could use them.
>
> With the 'beginner's luck' the first angiography performed with this technique was a success: a subclavian arteriography, with one single exposure, the catheter introduced through the brachial artery after puncture at the cubital level, which revealed a parathyroid adenoma, unsuccessfully searched for by the surgeon in the mediastinum,
>
> With my permission, the Head of the Department, Knut Lindblom, reported on the technique at the Radiological Congress of Northern Europe which took place in Helsinki one week later, in June 1952.
>
> Seldinger (1987)

The January 1984 issue of the *American Journal of Roentgenology* [36] (volume 142) celebrated the 30th anniversary of the Seldinger Technique with a series of articles on Seldinger [37]. The article by Doby (1984) gives an excellent historical overview, and includes some detailed sketches by Seldinger himself relating to his development of the technique.

Stanley Baum and Herbert Abrams

A not uncommon problem associated with the straight guidewire, particularly when cannulating the femoral artery, was failure to advance easily. This problem was largely overcome in 1964 by Baum and Abrams' development of the J-tipped catheter which is threaded over the guidewire (Baum and Abrams 1964). Once the catheter has been

[35] Phocion (402–317 B.C.): Athenian statesman, general, and pupil of Plato.

[36] See their web site at http://www.ajronline.org/ Most are are on the thoracic anaesthesia CD.

[37] The main articles are listed in the references.

positioned above the obstruction then the catheter is changed (by reinserting the guidewire) for a special angiography catheter.

Charles Dotter

At approximately the same time the American radiologist Charles Dotter (1920–1985), widely regarded as the father of interventional radiology, was beginning to lay the foundations of this new speciality at the Oregon Health State University,[38] in conjunction with his student Melvin Judkins.

In 1963 Dotter inadvertently unblocked an occluded right iliac artery while passing a catheter through it in order to reach the aorta for an abdominal aortogram, and realised that intravascular catheterisation can be used therapeutically as well as diagnostically. On 16 January 1964, Dotter, together with Judkins, performed the first deliberate dilation of an arterial obstruction, and thereafter developed the tools and techniques for what is now known as transluminal angioplasty (Payne 2001). Dotter also developed the first safety J-tipped guidewire (Judkins *et al.* 1967), flow-guided catheter, an intravascular biopsy catheter, and intravascular coils which were the forerunner of expandable stents (http://www.ohsu.edu/dotter/ctdotter.htm).

PICC catheters—Broviac JW and Hickman

With the advent of intensive care, intravenous nutrition and chemotherapy central catheters were increasingly used for long periods of time, leading to significant catheter-related infections. This prompted engineers to address design and materials issues, leading to new long-term so-called PICC catheters,[39] first by Broviac *et al.* (1973) and later by Hickman *et al.* (1979). Special valved catheters (Croshong catheter) were developed by Bard Access Systems.

9.6.2 References

- Baum S and Abrams HL (1964). A J-shaped catheter for retrograde catheterization of tortuous vessels. *Radiology*; 83, 436–437. [first description/use of the J-catheter]
- Broviac JW, Cole JJ and Scribner BH (1973). A silicone rubber atrial catheter for prolonged parenteral alimentation. *Surg. Gynaecol. Obstet.*; 136, 602–606.
- Cournand AF (1956). Control of the pulmonary circulation in man with some remarks on methodology. (Nobel Lecture)
- Doby T (1984). A tribute to Sven-Ivar Seldinger. *American Journal of Roentgenology*; 142 (Jan), 1–3. [http://www.ajronline.org/cgi/reprint/142/1/1.pdf]

[38] see http://www.ptca.org/nv/history.html, and also http://www.ohsu.edu/dotter/

[39] PICC — Peripherally Inserted Central Catheter.

- Forssmann W (1929). Catheterization of the right heart. *Klinische Wochenschrift*; 8 (No. 45), 2085–2087. [from Luft 1994]
- Greitz T (1999). Sven-Ivar Seldinger. *Am. J. Neuroradiol.*; 20 (June/July), 1180–1181. [http://www.ajnr.org/cgi/content/full/20/6/1180]
- Harris P, Fritts HW, Clauss RH, Odell JE and Cournand A (1956). Influence of acetylcholine on human pulmonary circulation under normal and hypoxic conditions. *Proc. Soc. Exptl. Biol. Med.*; 93, 77.
- Higgs ZCJ, Macafee DAL, Braithwaite BD and Maxwell-Armstrong CA (2005). The Seldinger technique: 50 years on. *Lancet*, 366, 1407–1409.
- Judkins M, Kidd HJ *et al.* (1967). Lumen-following J-guide for catheterization of tortuous vessels. *Radiology*; 88, 1127.
- Luft FC (1994). The birth of a common procedure. *Annals of Internal Medicine*; 120, 974.
- Payne MM (2001). Charles Theodore Dotter, the father of intervention. *Texas Heart Institute Journal*; 28, 28–38. http://www.tmc.edu/thi/thiaward.html
- Richards DW (1956). The contribution of right heart catheterization to physiology and medicine, with some observations on the pathophysiology of pulmonary heart disease. (Nobel Lecture)
- Seldinger SI (1953). Catheter replacement of the needle in percutaneous arteriography: a new technique. *Acta Radiologica Scandinavica*; 39, 368–376.
- Seldinger SI (1987). *A leaf out of the history of angiography*.
  In: Silvestre ME, Abecasis F and Veiga-Pires JA (1987); *Radiology: Faculty Proceedings of the 6th European Congress of Radiology, Lisbon, Portugal, 31 May–6 June 1987.* (Excerpta Medica, International Congress Series No. 749; Elsevier Science Publishers BV [Biomedical Division], Amsterdam, The Netherlands.) ISBN: 0-444-80947-3. p. 3–6. [from Greitz (1999)]
- (1984) — special 'Seldinger' issue of the *American Journal of Roentgenology*; 142 (Jan):
  - Sven-Ivar Seldinger: a biography and bibliography. *American Journal of Roentgenology*; 142 (Jan), 4.
  - The Seldinger technique. *American Journal of Roentgenology*; 142 (Jan), 5–7. [a reproduction of Seldinger's original article]
  - Testimonials to Seldinger. *American Journal of Roentgenology*; 142 (Jan), 8–11. [reflections by Dotter CT, Grainger RG, Nordenström B, Abrams HL, and Athanasoulis CA]

9.6.3 Optimum position

The current view regarding the optimum location of the tip of a CVP-catheter is driven by the need to avoid the possibility of the catheter migrating into the pericardium. Consequently the tip should be *above* the pericardial reflection on to the SVC (Chalkiadis and Goucke 1998), which is generally held to be at the level of the carina (T4–T5; sternal angle)—i.e., above the left and right atria. Ryu *et al.* (2007) give a simple landmark-based method for safely positioning the tip of the CVP line in relation to the carina. Several articles have appeared recently describing the use of ultrasound to facilitate CVP-line placement, including a good editorial by Scott (2004).

Techniques for correcting/relocating subclavian and internal-jugular catheters which have taken an aberrant course are addressed by Pattnaik and Bodra (1999); they highlight an article by Kayal *et al.* (1989) who used ultrasound while flushing with saline to detect when the tip of the catheter is in the correct vessel. Pattnaik and Bodra (1999) suggest listening with a stethoscope is useful. An alternative approach to the 'aberrant catheter' problem, might be to consider placing a new J-wire into the same vein via the proximal lumen [40] (hopefully in the internal jugular vein), removing the misplaced CVP line and then railroading a new one—with luck the new wire will be in a better location (one could check the new wire position with an x-ray first perhaps).

Occasionally a CVP line inserted via the left IJ vein will go down the left internal mammary vein; quite how this happens is not clear since the curved tip of the J-wire should prevent the wire from going down a small vessel. The distal lumen in such cases is typically associated with difficult aspiration and poor CVP waveform. Since redirecting a misplaced CVP line can be difficult, consider monitoring the CVP via one of the more proximal lumens—withdrawing the line slightly if necessary—until you see a good CVP waveform. Consequently, always X-ray a left IJ line *before* considering railroading a Swan-sheath over it. For information and video clips relating to CVP insertion technique see the Clinical Cases web-site (http://clinicalcases.blogspot.com).

9.6.4 Anatomy

- Albrecht K *et al.* (2004). Applied anatomy of the superior vena cava—the carina as a landmark to guide central venous catheter placement. *Br. J. Anaesth.*; 92, 75–77.
- Davidson A, Blumgard C, Paes ML and Enever G (1993). Posture and internal jugular vein size studied with the 'Siterite' ultrasound device. *Br. J. Anaesth.*; 71, 771P. [November issue]
  [gives a useful table of depth and diameter of the vein for various amounts of head tilt. My own working of their data gives the mean depth of the middle of the vein as 1·64 cm, which is equivalent to a distance of 2·3 cm at 45 degrees to the skin]

[40] I have not tried this as yet, but it seems as though it ought to work.

- Daseler EH and Anson BJ (1959). Surgical anatomy of the subclavian artery and its branches.*Surg. Gynecol. Obstet.*; 108, 149–174.
- Galloway S and Bodenham A (2003). Ultrasound imaging of the axillary vein—anatomical basis for central venous access. *Br. J. Anaesth.*, 90, 589–595.
- Mathers LH, Smith DW and Frankel L (1992). Anatomic considerations in placement of central venous catheters. *Clinical Anatomy*; 5, 89–106.
- Pahwa R and Kumar A (2003). Persistent left superior vena cava: an intensivist's experience and review of the literature. *Southern Medical Journal*; 96, 528–529. [see example CXR on the http://www.learningradiology.com/ website (search for 'persistent left superior vena cava')]
- Latto IP, Ng WS, Jones PL and Jenkins BJ [Eds.] (2000). *Percutaneous central venous and arterial catheterisation*; 3rd ed, (W. B. Saunders Company Ltd., London, UK).
- Schummer W, Schummer C and Fröber R (2003). Internal jugular vein and anatomic relationship at the root of the neck. *Anesthesia and Analgesia*; 96, 1540.
- Schummer W, Schummer C and Geold M (2002). Persistent left superior vena cava: clinical implications for central venous cannulation. *American Society for Parenteral and Enteral Nutrition*; 17, 304–308.
- Sulek CA, Gravenstein N, Blackshear RH and Weis L (1996). Head rotation during internal jugular vein cannulation and the risk of carotid artery puncture. *Anesthesia and Analgesia*; 82, 125–128. [keeping the head in the midline position reduces the incidence of carotid artery puncture]

9.6.5 Position of CVP tip

- Albrecht K *et al.* (2004). Applied anatomy of the superior vena cava—the carina as a landmark to guide central venous catheter placement. *Br. J. Anaesth.*; 92, 75–77.
- Chalkiadis GA and Goucke CR (1998). Depth of central venous catheter insertion in adults: an audit and assessment of a technique to improve tip position. *Anaesthesia and Intensive Care*; 26, 61–66. [they used the subclavian method—their tailored technique (8 cm distal from the tip of needle) gave a mean distance from the skin of 13·2 cm (range: 11·5–15 cms; n=73)]
- Rath GP, Bithal PK, Toshniwal GR, Prabhakar H and Dash HH (2009). Saline flush test for bedside detection of misplaced subclavian catheter into ipsilateral internal jugular vein. *Br. J. Anaesth.*, 102, 499-502.
- Ryu H-G, Bahk J-H, Kim J-T and Lee J-H (2007). Bedside prediction of the central venous-catheter insertion depth. *Br. J. Anaesth.*, 98, 225–227.

9.6.6 General

- Chalkiadis GA and Goucke CR (1998). Depth of central venous catheter insertion in adults: an audit and assessment of a technique to improve tip position. *Anaesthesia and Intensive Care*; 26, 61–66. [they used the subclavian method—their tailored technique (8 cm distal from the tip of needle) gave a mean distance from the skin of 13·2 cm (range: 11·5–15 cms; n=73)]
- Fukazawa K, Aguina L and Pretto E (2010). IMAGES IN ANESTHESIOLOGY: Internal jugular valve and central placement. *Anesthesiology*; 112, 979.
- Kayal RD, Salloum LJ, Snyder AB and Barone JE (1989). A simple method of repositioning the wayward central catheter. *Journal of Parenteral and Enteral Nutrition*; 13, 438–439.
- Kitagawa N *et al.* (2004). Proper shoulder position for subclavian venepuncture. *Anesthesiology*; 101, 1306–1312. [evidence from CT studies suggests that best position is with the shoulder pushed inferiorly]
- Messahel FM and Al-Mazroa AA (1992). Cannulation of the internal jugular vein; the very high approach. *Anaesthesia*; 47, 842–844.
- Nandwani N, Fairfield MC, Krarup K and Thompson J (1997). The effect of laryngeal mask airway insertion on the position of the internal jugular vein. *Anesthesia*; 52, 77–83. [no lateral movement, but perhaps some slight anterior movement 0·6–1·1 cm, mean 0·8 cm]
- Ng PK, Ault MJ and Maldonaldo LS (1996). Peripherally inserted central catheters in the intensive care unit [review]. *J. Intensive Care Medicine*; 11, 49–54.
- Oropello JM, Leibowitz AB, Manasia A, Guidice RD and Benjamin E (1996). Dilator associated complications of central vein catheter insertion: possible mechanisms of injury and suggestions for prevention. *Journal of Cardiothoracic and Vascular Anesthesia*; 10, 634–637.
- Pattnaik SK and Bodra R (1999). Another 'whoosh' test. *Anaesthesia*; 54, 1224–1225. [they describe gradually withdrawing the the malpositioned central line while listening for the disappearance of the distal 'whoosh' sound (caused by flushing it with saline) with a stethoscope over the vein. Also list other useful references on this theme (6 refs)].
- Latto IP, Ng WS, Jones PL and Jenkins BJ [Eds.] (2000). *Percutaneous central venous and arterial catheterisation*; 3rd ed, (W. B. Saunders Company Ltd., London, UK).
- Sha K *et al.* (1998). Use of transoesophageal echocardiography probe imaging to guide internal jugular vein cannulation. *Anesthesia & Analgesia*, 87, 1032–1033.

- Stickle BR and McFarlane H (1997). Prediction of a small internal jugular vein by external jugular vein diameter. *Anaesthesia*, 52, 220–222.
  [if the external jugular vein is greater than 7 mm diam, then the internal jugular vein is likely to have a diameter less than 7 mm, and so may be difficult to find]
- Tripathi M, Dubey PK and Ambesh SP (2005). Direction of the J-tip of the guidewire in Seldinger technique is a significant factor in misplacement of subclavian vein catheter: a randomised controlled study. *Anesthesia and Analgesia*; 100, 21-24.
- Tripathi M and Tripathi M (1996). Subclavian vein cannulation: an approach with definite landmarks. *Ann. Thoracic Surgery*; 61, 238–240.
- Willeford KL and Reitan JA (1994). Neutral head position for placement of internal jugular vein catheters. *Anaesthesia*; 49, 202–204.
- Williamson RM and Werstler E (2006). Central line in patients with AV fistula. *Anaesthesia*; 61 (August), 819-820. [describes confusion with the sampled blood gases in a renal patient with a left-arm dialysis fistula]

9.6.7 Ultrasound guided

- Chapman GA, Johnson D and Bodenham AR (2006). Visualisation of needle position using ultrasonography. *Anaesthesia*; 61, 148–158.
- Fukazawa K, Aguina L and Pretto E (2010). IMAGES IN ANESTHESIOLOGY: Internal jugular valve and central placement. *Anesthesiology*; 112, 979.
- Galloway S and Bodenham A (2003). Ultrasound imaging of the axillary vein—anatomical basis for central venous access. *Br. J. Anaesth.*, 90, 589–595.
- Habib FA and McKenney MG (2004). Surgeon-performed ultrasound in the ICU setting. *Surgical Clinics of North America*; 84, 1151–1179. [see section on CVP line placement 1165–1166, with screen images]
- Hall AP and Russell WC (2005). Towards safer central venous access: ultrasound guidance and sound advice. *Anaesthesia*; 60, 1–4. [see also correspondence from Reavley P (2005)]
- Hatfield A and Bodenham A (2005). Ultrasound for central venous access. *Continuing Education in Anaesthesia, Critical Care & Pain*; 5, 187–190.
- National Institute for Clinical Excellence (NICE) (2002). Guidance on the use of ultrasound locating devices for placing central venous catheters. Technical Appraisal Guidance 2002, **49**. http://www.nice.org.uk/pdf/ultrasound_49_GUIDANCE.pdf [see also: Proposal to move guidance to the static list (NICE, 2005) http://www.nice.org.uk/pdf/ta049reviewproposal.pdf]

- Riopelle JM, Ruiz DP, Hunt JP *et al.* (2005). Circumferential adjustment of ultrasound probe position to determine the optimal approach to the internal jugular vein: a noninvasive geometric study in adults. *Anesth. Analg.*; 100, 512–519.
- Scott DHT (2004). The king of the blind extends his frontiers. *Br. J. Anaesth.*; 93, 175–177. [editorial on ultrasound-guided techniques]

9.6.8 External jugular vein

If the external jugular vein distends on head-down position, then a Venflon in this site adequately reflects CVP providing the chest is not open. Placing a central catheter via this route has a high failure rate.

- Blitt CD, Wright WA, Petty WC and Webster TA (1974). Central venous catheterisation via the external jugular vein. A technique employing the J-wire. *JAMA*; 229, 817.
- Briscoe CE (1973). A comparison of jugular [external] and central venous pressure measurement during anaesthesia. *Br. J. Anaesth.*; 45, 173.
- Dailey RH (1988). External jugular vein cannulation and its use for CVP monitoring. *Journal of Emergency Medicine*; 6, 133.
- Shah MV, Swai EA and Latto IP (1986). Comparison between pressures measured from the proximal external jugular vein and a central vein. *Br. J. Anaesth.*; 58, 1384.

9.6.9 Axillary vein

- Andel H, Rab M, Felfernig M *et al.* (1999). The axillary vein central venous catheter in severely burned patients. *Burns*; 25, 753–756.
- Galloway S and Bodenham A (2003). Ultrasound imaging of the axillary vein—anatomical basis for central venous access. *British Journal of Anesthesia*, 90, 589–595.
- Levine E and Budzikowski AS (2009). Catheterisation, axillary vein.
  http://emedicine.medscape.com/article/1348912-overview
  http://emedicine.medscape.com/article/1348912-media
  http://emedicine.medscape.com/article/1348912-treatment
  (other related procedures are at: >clinical_procedures>vascular)
  Accessed May 2010.
- Nickalls RWD (1987). A new percutaneous infra-clavicular approach to the axillary vein. *Anaesthesia*; 42, 151–154. http:/www.nickalls.org/dick/papers/anes/axillaryvein1987.pdf

- Restrepo Valencia CA (2008). Axillary catheter for hemodialysis, an alternative vascular access. *Nefrologia*;, 28, 77–81.
- Sandhu NS (2004). Transpectoral ultrasound-guided catheterization of the axillary vein: an alternative to standard catheterization of the subclavian vein. *Anesthesia and Analgesia*; 99, 183–187.
- Sharma A, Bodenham AR and Mallick A (2004). Ultrasound-guided infraclavicular axillary vein cannulation for central venous access. *Br. J. Anaesth.*; 93, 188-192.
- Taylor BL and Yellowlees I (1990). Central venous cannulation using the infraclavicular axillary vein. *Anesthesiology*; 72, 55.

9.6.10 Femoral vein

There are many papers in the literature showing that CVP is accurately reflected by inferior vena cava and common iliac venous pressure measurements in supine patients (both adult and paediatric), providing the transducer is zeroed at the usual right-atrial level on the mid-axillary line. Measurements of inferior vena cava pressures seem to be approximately 0·5 mm Hg lower than superior vena cava pressures on average, and rarely more than 3 mm Hg different, even in patients with high PEEP or raised mean airway pressures (Desmond 2003). Femoral CVP results may be less accurate in patients with significantly raised intra-abdominal pressure [the references below are from Desmond (2003)].[41]

- Chait HI, Kuhn MA, Baum VC (1994). Inferior vena caval pressure reliably predicts right atrial pressure in pediatric cardiac surgical patients. *Crit. Care Med.*; 22, 219–24.
- Desmond J (2003). Is the central venous pressure reading equally reliable if the central line is inserted via the femoral vein? http://www.bestbets.org/ [critical care section]
- Ho KM, Joynt GM, Tan P. (1998). A comparison of central venous pressure and common iliac venous pressure in critically ill mechanically ventilated patients. *Crit. Care Med.*; 26, 461–4.
- Nahum E, Dagan O, Sulkes J, *et al.* (1996). A comparison between continuous central venous pressure measurement from right atrium and abdominal vena cava or common iliac vein. *Intensive Care Med.*; 22, 571–4.
- Joynt GM, Gomersall CD, Buckley TA, *et al.* (1996). Comparison of intrathoracic and intra-abdominal measurements of central venous pressure. *Lancet*; 347, 1155–7.
- Walsh JT, Hildick-Smith DJ, Newell SA, *et al.* (2000). Comparison of central venous and inferior vena caval pressures. *Am. J. Cardiol.*; 85, 518–20.

[41] I thank Dr Mofolashade Enebeli-Cliffe for drawing my attention to many of these references.

9.6.11 Complications

These are mostly related to air embolism, vessel damage from needle or dilator or kinked guide-wire, introducing the guide-wire *outside* the vessel, catheter knotting, dysrhythmias, pneumothorax and cardiac tamponade. Unusual anatomy [42] and failure to use ultrasound visualisation appear to be prominent factors in many complications (see Section 9.6.4).

Guide-wire problems

The guide-wire is easily kinked, and once kinked it can not be straightened and can easily damage/tear the vein if introduced into it. A simple test to check for such kinking while trying to advance the dilator (over the wire) is to intermittently check that you can slide the wire back and forth (say, ± 1 cm or so) inside the introducer. Any difficulty in sliding the wire back and forth is a good sign that the wire may have become kinked—in which case withdraw the guide-wire carefully to bring the kink to the skin for inspection.

In my experience, the guide-wire is most easily damaged/kinked when using the femoral approach in fat patients, since in these cases one often has to press the Sonosite probe down quite firmly (and hence distort the subcutaneous tissue) in order to see the vein clearly. The kinking of the guide-wire usually occurs while trying to introduce the dilator through the subcutaneous tissue, since in fat patients the path of the guide-wire here becomes quite curved into a sigmoid shape *once the Sonosite probe is removed*.[43] In my experience in this setting, it is best to have an assistant replace the Sonosite probe and press down as before (i.e., to straighten the subcutaneous path of the guide-wire) while introducing the dilator.

If a dialysis catheter guide-wire does become kinked in a difficult case, it is often possible to rescue the situation and exchange it safely, since the guidewire will generally still be in the vein even when pulled back slightly to bring the kink to the skin [44]. The idea is to first railroad an ordinary CVP line over the wire and into the vein (ie., with the kink still showing just above the skin), replace the damaged guide-wire with a new dialysis catheter guide-wire, then remove the CVP line, and then continue with the dialysis line as before.

- Dhanani J, Senthuran S, Olivotto R, Boots RJ and Lipman J (2007). The entrapped central venous catheter. *Br. J. Anaesth.*; 98, 89–92.
  [a new catheter pierced an existing catheter in the same vein; interventional radiology used for diagnosis and determination of a removal strategy; the literature is reviewed; 11 refs]

[42] Persistence of the left superior vena cava (LSVC)—which is asymptomatic—is thought to be the most common anomaly of the venous circulation and can be a significant hazard with regard to CVP line placement (see paper by Schummer, Schummer and Gerald(2002) listed in Section 9.6.4).

[43] Since the guide-wire is initially introduced via a straight needle, its path to the vein will only remain straight (after removing the needle) *while the Sonosite probe is pressing down over the vein*.

[44] It is therefore, a good idea to introduce plenty of guide-wire into the vein before starting to thread the dilator.

- Lobato EB, Gravenstein N and Paige GB. (1997). Dilator-associated complications of central vein catheter placement: possible mechanisms of injury and suggestions for prevention. *Journal of Cardiothoracic and Vascular Anesthesia*; 11, 539.
- Muhn M, Sunder-Plassmann G and Druml W (1996). Malposition of a dialysis catheter in the accessory hemiazygos vein. *Anesthesia and Analgesia*; 83, 883-885.
- Oropello JM, Leibowitz AB, Manasia A, Guidice RD and Benjamin E (1996). Dilator-associated complications of central vein catheter placement: possible mechanisms of injury and suggestions for prevention. *Journal of Cardiothoracic and Vascular Anesthesia*; 10, 634–637.
- Jiha JG, Weinberg GL and Laurito CE (1996). Intraoperative cardiac tamponade after central venous cannulation. *Anesthesia and Analgesia*; 82, 661–665.
- Scott WL and Collier P (2001). The vessel dilator for central venous catheter placement: forerunner for success or vascular misadventure? *Journal of Intensive Care Medicine*; 16, 263–269.

9.7 Pulmonary artery catheter

9.7.1 History

Michael Lategola and Hermann Rahn

Balloon-flotation pulmonary artery catheters were first used by the American physiologists Lategola and Rahn for pressure recording, blood sampling and vessel occlusion in experiments with dogs (Lategola and Rahn 1953). Since their balloon covered the distal tip they were only able to measure pressures proximal to the occluded vessel. Thermodilution cardiac output was first described in animals the following year (Fegler 1954).

Ronald Bradley

The first person to describe the use of a pulmonary-artery catheter in man was Ronald Bradley, a physician at St. Thomas' Hospital, London (Bradley 1964). He used an extremely narrow catheter (0·63 mm diam) having no balloon, to determine pulmonary artery pressures and waveforms, and later went on to determine thermodilution cardiac output in man using a thermistor-tipped catheter (Branthwaite and Bradley 1968), and suggested the use of PA-diastolic pressure as an index of mean left-atrial pressure (Jenkins, Bradley and Branthwaite 1970). Bradley also wrote an excellent book on the physiology of heart failure (Bradley 1977).

Harold Swan and William Ganz

Bradley's catheters had no balloon and were extremely difficult to position, and so the technique remained clinically impractical until Swan *et al.* (1970) developed the modern balloon-flotation catheter. Since Swan wished to determine left atrial pressure he arranged that pressures could be measured distal to the balloon. Oddly enough Swan fails to credit Bradley and Branthwaite (1968) with the thermodilution technique in man—instead he credits this to Ganz (Swan 1991).

Swan (1922–2005) graduated from St. Thomas' Hospital Medical School, London, in 1945, and went on to become the Director of the Division of Cardiology at Cedars-Sinai Medical Center in Los Angeles, California. He has set on record the key early ideas and development of the flow-directed balloon-tipped catheter (Swan 1991; 2005) as follows.

> In 1950 as a lecturer in physiology at St. Thomas' Hospital of the University of London, I had come to know a young medical student, Ronald Bradley, who was completing a bachelor's degree in physiology. I had noted a paper published in the *Lancet* (Bradley 1964), in which Bradley had claimed that it was possible to catheterize the pulmonary artery for measurement of pressures using an extremely fine Portex tubing ... and I therefore attempted to place it. ... In our hands this approach had little success ...
>
> In the fall of 1967, I had the occasion to take my (then young) children to the beach in Santa Monica. On the previous evening, I had spent a frustrating hour with an extraordinary pleasant but elderly lady in an unsuccessful attempt to place one of Bradley's catheters. It was a hot Saturday and the sailboats on the water were becalmed. However, approximately half a mile offshore, I noted a boat with a large spinnaker well set and moving through the water at a reasonable velocity. The idea then came to to put a sail or a parachute on the end of a highly flexible catheter and thereby increase the frequency of passage of the device into the pulmonary artery. I felt convinced that this approach would allow for the rapid and safe placement of a flotation catheter without the use of fluroscopy and would solve the problem of arrhythmias.
>
> ... I had been appointed a consultant to the Edwards Laboratories, then a small manufacturing company whose products included the Starr-Edwards heart valve and the Fogarty embolectomy catheter. ... I brought my concept to the attention of Mr David Chonette and Mr Will Perrie. They had the facilities for extrusion of catheters of different sizes ... To test the concept, however, they had the ability to manufacture balloons (as for the Fogarty catheter) and suggested that, as a first effort, a double-lumen extruded catheter should be manufactured with one lumen available to inflate a flotation balloon. This proved to be acceptable and they agreed to fabricate five such catheters.
>
> ... As luck would have it, when the Edwards Laboratories delivered their first catheters, Willie [Ganz] was finishing an experiment with his animal in good condition. I brought the prize catheters to the laboratory and connected the pressure lumen to an appropriate strain gauge manometer. The catheter was then introduced via the exposed jugular vein into the right atrium and, observing with fluroscopy, the balloon was inflated. It immediately disappeared, and the technician reported no change in the recorded pressure. I immediately assumed an inadequacy of balloon tensile strength and mentally

> blamed faulty construction by the Edwards Laboratory. However, repeat visualization revealed that the catheter had migrated in one heartbeat through the right heart and was recording the wedge pressure in a distal pulmonary artery. Deflation of the balloon allowed its prompt return to the superior vena cava. ... Willie Ganz accepted the responsibility of clearing up the many technical details, but the concept was proved and the new device was born.
>
> ... A triple-lumen catheter allowed measurement of simultaneous pressures in the wedge position (the pulmonary occluded pressure) and in the right atrium. With a slight modification, a thermistor was inserted close to the guiding balloon and the thermodilution technique of Willie Ganz (Ganz *et al.* 1971) for determination of cardiac output was applied.
>
> Swan (1991)

Swan (1922–2005) died on 7th February, 2005, and his last paper (Swan 2005) appeared in the October 2005 issue of *Anesthesiology*. A photograph of Swan can be found on the *Anesthesiology* web site.[45]

- Achan V (1999). Another European view: the origin of pulmonary artery catheterization. *Critical Care Medicine*; 27, 2850–2851.
- Amin DK, Shah PK and Swan HJC (1986). The Swan-Ganz catheter: choosing and using the equipment. *Journal of Critical Illness*; 1, 34–37.
- Amin DK, Shah PK and Swan HJC (1986). The Swan-Ganz catheter: insertion technique. *Journal of Critical Illness*; 1, 38–45.
- Amin DK, Shah PK and Swan HJC (1986). The Swan-Ganz catheter: tips on interpreting results. *Journal of Critical Illness*; 1, 40–48.
- Amin DK, Shah PK and Swan HJC (1986). The Swan-Ganz catheter: indications for insertion. *Journal of Critical Illness*; 1, 54–61.
- Bradley RD (1964). Diagnostic right-heart catheterisation with miniature catheters in severely ill patients. *Lancet*; 2, 941–942.
- Bradley RD (1977). *Studies in acute heart failure*. (Edward Arnold Ltd., London). ISBN: 0–7131–4295–2. pp. 76.
- Branthwaite MA and Bradley RD (1968). Measurement of cardiac output by thermal dilution in man. *J. Applied Physiology*; 24, 434–438.
- Comroe JH (1977). *Retrospectroscope: insights into medical discovery*. (Von Gehr Press, Menlo Park, California, USA).

[45] http://www.anesthesiology.org; follow the 'enhancements index' link → 2005.

- Fegler G (1954). Measurement of cardiac output in anesthetized animals by a thermodilution method. *Quarterly Journal of Experimental Physiology*; 39, 153–164. [from: MacKenzie 2003]
- Ganz W, Donoso R, Marcus HS, Forrester JS and Swan HJC (1971). A new technique for measurement of cardiac output by thermodilution in man. *American Journal of Cardiology*; 27, 392–396.
- Jenkins BS, Bradley RD and Branthwaite MA (1970). Evaluation of pulmonary arterial end diastolic pressure as an indirect estimate of left atrial mean pressure. *Circulation*; 42, 75.
- Lategola M and Rahn H (1953). A self-guiding catheter for cardiac and pulmonary arterial catheterization and occlusion. *Proc. Soc. Exp. Biol. Med.*; 84 667–668.
- Poplausky MR, Rozenblit G, Rundback H *et al.* (2001). Swan-Ganz catheter-induced pulmonary artery pseudoaneurysm formation: three case reports and a review of the literature. *Chest*; 120, 2105–2111.
- Shaw TJI (1979). The Swan-Ganz pulmonary artery catheter: incidence of complications, with particular references to ventricular dysrhythmias, and their prevention. *Anaesthesia*; 34, 651–656. [recommends use of lignocaine 1mg/kg IV]
- Swan HJC (2005). The pulmonary artery catheter in anesthesia practice. *Anesthesiology*, 103, 890-893. [Swan's final paper—includes some interesting historical detail regarding the development of the PA catheter]
- Swan HJC (1991). Development of the pulmonary artery catheter. *Disease-a-Month*; 37 (August), 485–508 (Elsevier). [whole of this classic issue (p. 478–543) is devoted to the Swan-Ganz catheter, including a reprint of the excellent four-part series by Amin, Shah and Swan (1986) listed below. Available on-line via http://www.sciencedirect.com/ & also via the ATHENS internet database]
- Swan HJC, Ganz W, Forrester J, Marcus H, Diamond G and Chonette D (1970). Catheterization of the heart in man with use of a flow-directed balloon-tipped catheter. *New England Journal of Medicine*; 283, 447–451.

9.7.2 Decline in use

In recent years the use of pulmonary artery catheters has declined somewhat, partially owing to lack of good evidence that it improves outcome (ESCAPE committee 2005; Shah *et al.* 2005; Hall 2005), and partly owing to new non-invasive cardiac output monitoring devices (e.g., PiCCO, LiDCO, oesophageal doppler).

- ASA (2003). Practice guide-lines for pulmonary artery catheterisation: an updated report by the American Society of Anesthesiologists Task Force on pulmonary artery catheterisation. *Anesthesiology*; 99, 988–1014.

- ESCAPE committee (2005). Evaluation study of congestive heart failure and pulmonary artery catheter effectiveness: the ESCAPE trial. *JAMA*; 294, 1625–1633.
- Hall JB (2005). Searching for evidence to support pulmonary artery catheter use in critically ill patients. *JAMA*; 294, 1693–1694.
- Shah MR *et al.* (2005). Implication of the pulmonary artery catheter in critically ill patients: meta-analysis of randomized clinical trials. *JAMA*; 294, 1664–1670.

9.8 Computers & information technology

The first anaesthetic machine to incorporate a microprocessor was in 1976 (Katz 2006), and since then computers have progressively influenced anaesthesia delivery and patient safety. One of the next major influences on anaesthesia practice is likely to be related to data processing, particularly in the areas of smart alarms and decision support. While development and take-up in the operating theatre is almost imperceptible just now, the future surely lies in computers offering anaesthetists seriously useful facilities. The initial motivation with regard to data handling lay in automating the anaesthesia record. However, while this technology has been effectively solved for over 15 years (see Kenny 1990), the take-up by anaesthetists in the UK remains almost zero.

9.8.1 History of the anaesthesia record

The documentation of events, procedures undertaken, physiological parameters (*vital signs*) which are associated with the process of anaesthesia (for example, in conjunction with surgery or an intensive care setting) is known as the Anaesthesia Record. This record serves two main functions, namely (a) medical (the moment-to-moment drug history and vital-signs serves as a useful practical aid), and (b) medico-legal (the anaesthesia record is a legal document in its own right, setting out the facts as they unfold during an anaesthetic).

Background

Effective surgical anaesthesia using inhaled diethyl-ether ("*ether*") was first established in 1842 by Crawford Long (1815–1878) in a handful of unpublicised cases. Some four years later in 1846 ether anaesthesia was rediscovered and popularised by William Morton (1819–1868), who gave a public demonstration on 16th October 1846 at the Massachusetts General Hospital (Boston, USA).

Subsequently, John Snow (1813–1858), Joseph Clover (1825–1882), and Mounier (1855) demonstrated the importance of monitoring the pulse and respiration during anaesthesia (Ellis 1995; Rushman, Davies and Atkinson 1996), but it was not until 1894, at the Massachusetts General Hospital, Boston, that surgeons Ernst A Codman (1869–1940) and Harvey Cushing (1869–1939) established the practice of keeping a careful *written* record (on graph paper) of the patient's pulse and respiration rate during operations—known as

the 'ether chart' (Beecher 1940; Hirsch and Smith 1986). Apparently this was prompted by a death under anaesthesia in 1893 (Rushman, Davies and Atkinson 1996, p. 128). In 1901 they started including measurements of the arterial blood pressure using the newly described apparatus of Scipione Riva-Rocci (1863–1937) of Turin (Cushing 1902; Cushing 1903; Rushman, Davies and Atkinson 1996, p. 157).

Ralph Waters (1936; 1942) championed and emphasised the importance of written anaesthetic records, and later Noseworthy (1945) produced special cards on which to record anaesthetic details (see Rushman, Davies and Atkinson 1996, p. 111, for an illustration).

Automation

An automated anaesthesia record is significantly superior to the usual hand-written record, since it samples data much more frequently and more accurately, and hence it has significant medico-legal advantages regarding the documentation of patient care, particularly during complicated and/or unstable cases.

The first mechanical device capable of printing an anaesthetic record was the *Nargraf* machine of 1930 developed by EI McKessons (Westhorpe 1989), which generated a semi-automated record of inspired oxygen, tidal volume and inspiratory gas pressure.

After this little of real technological significance was developed in the area of anaesthesia monitoring until the 1970s, when advances in chip technology gave rise to clinically useful portable electronic devices for measuring such things as arterial and central venous blood pressure, breath-by-breath concentrations of oxygen, carbon dioxide and inhalational anaesthetics, pulse oximetry, and of course, small computers.

From an interfacing point of view, a very significant and far reaching feature was incorporated into virtually all early medical monitoring devices, namely a specialised serial communications interface known as the RS-232 port.[46] Equally significant, therefore, was the decision by IBM to incorporate the RS-232 port into the IBM Personal Computer which appeared in 1981. Fortunately all IBM-compatible PCs since then have also incorporated the RS-232 serial port.

Owing to the widespread use of the RS-232 interface in medical equipment it soon became a relatively easy matter to use a PC to access the numerous measured and derived parameters output by patient monitoring devices, and consequently anaesthetists increasingly explored methods for automating data collection and processing, with a view to developing useful trend displays of measured data, real-time calculation of derived parameters, and hard-copy data printouts.

The RS-232 interface is likely to be replaced at some stage by the Medical Interface Bus (MIB; IEEE-1073). This is a high-tech high-speed medical plug-and-play version of the familiar domestic USB interface, and will greatly facilitate medical device inter-connectivity, largely by allowing the relevant interface software to be more easily standardised.

[46]The Electronic Industries Association Recommended Standard 232. In 1986 the prefix RS was superceded by the prefix EIA. In 1988 the Telecommunications Industry Association (TIA) was formed by the merger of the US Telephone Suppliers Association and EIA/ITG, and subsequent documents are therefore prefixed by EIA/TIA. The 1991 revision was EIA/TIA-232-E. (Nickalls and Ramasubramanian 1995).

Guidelines

The Royal College of Anaesthetists has published a summary of what data ought to be collected (in addition to the electronic data from the anaesthesia monitors) as part of the Anaesthesia Record (Adams 1996), building on the work of Lack *et al.* (1994). The extent to which these guidelines are actually being met has also been looked at (Smith 1997). The required record set which appears to be emerging, consists of a number of fields within the following general categories: pre-, per- and postoperative information, untoward events and hazard flags.

9.8.2 The anaesthesia workstation

It is clear that computerisation, both in the operating theatre and in ITU, has the potential to free anaesthetists and nurses from much of the work of documentation (e.g., drug doses, procedures, measured parameters etc.), releasing significant amounts of time which is better spent on direct patient care. Anaesthesia Information Management Systems (AIMS) which incorporate sophisticated record-keeping systems clearly offer the advantage of allowing the anaesthetists to concentrate fully on the patient, leading to enhanced vigilance and improved patient care and safety.

Much work has gone into studying the anaesthetists's workload (Weinger *et al.* 1997; Byrne, Sellen and Jones 1998; Leedal and Smith 2005). For example, Kennedy *et al.* (1976) showed that anaesthetists commonly spend 10–15 % of their time producing the handwritten record. Similarly, Smith (1997) pointed out that about 10 % of the anaesthetists' time was related to record keeping, and that if this were to increase then this would likely be to the patient's detriment. A similar study by Wong *et al.* (2003) showed that an ICU information system reduced the time spent by nurses on documentation by 31 %, with the significant benefit being that almost half of the time saved was transferred to patient assessment and direct patient care.

Secondary data processing by anaesthetists in the UK is well behind other countries, with electronic data collection being actively supported by foreign health organisations. For example, in 2001 the 'summer' newsletter of the Anesthesia Patient Safety Foundation (APSF) was devoted to *Information systems in anaesthesia* (Thys, 2001). In 2002 the APSF formally endorsed the use of automated anesthesia information management systems (AIMS) as the following quote indicates (see also http://www.gasnet.org/societies/apsf/).

> In this context it is heartening that the ... APSF has recently endorsed the use of automated anesthesia information management systems (AIMS): "The Anesthesia Patient Safety Foundation endorses and advocates the use of automated record keeping in the perioperative period and the subsequent retrieval and analysis of that data to improve patient safety."
>
> Gage (2002)

Anaesthetists urgently need to harness the power of computing technology in a way which can help both in the operating theatre and in the clinic, most likely via some form

of anaesthesia workstation. While such systems will probably be commercial, this is not necessarily the only route. Providing anaesthetists take some interest in the details, it is quite possible for useful systems to be developed along the Open Source model, as for example, the immensely successful Linux operating system, and the excellent software tools TEX, LATEX, Perl and others.

The emphasis for such a workstation needs to be on helping the anaesthetist give a safe anaesthetic during difficult circumstances. It would access data from a range of sources via the Medical Interface Bus (e.g., anaesthesia monitors, HIS) and then process the data in various ways; for example, generating the anaesthesia record, offering smart alarms, decision support and predictive physiological and pharmacokinetic modelling, as well as enabling data export, data storage and emergency communications.

For a long time now, even with a modest PC, it has been a simple matter to access high quality data from anaesthesia monitors (Nickalls and Ramasubramanian 1995; Nickalls 1998, Nickalls, Dales and Nice 2010) and create excellent anaesthesia records offering medico-legal security. These are relatively straightforward to write and get up and running, as, for example, the graphic record shown in Figure **??** (page **??**) generated by the author's open-source anaesthesia workstation software.[47] With little additional work a theatre-based PC can also display warnings, equipment status information and value-added parameters; for example, real-time age-corrected MAC (Nickalls and Mapleson 2003), smart diabetes monitoring & management, as well as extensive general and drug information support (see Figure 9.5, page 151).

Although there has been widespread uptake of AIMS technology by anaesthetists, it is clear that the optimum interface design to facilitate easy and intuitive use is difficult to achieve. Interface design must minimise keyboard/mouse entries by the anaesthetists while maximising information display. All too often the user interface is awkward to use with the effect that time is wasted and data collection is incomplete (Driscoll *et al.*, 2007). However, since anaesthesia practice is much the same the world over, it is to be expcted that with sufficient computer-engineering research an optimum and intuitive interface will emerge given time. A typical example of current progress in making practical automated anaesthesia records and the involvement of XML is that described by Meyer-Bender *et al.* (2010). The wider adoption of AIMS technology also has the potential to bring about a significant reduction of intraoperative awareness (Nickalls and Mahajan 2010).

Of course commercial AIMS technology is available and can be extremely useful (for example, the NarKoData system [48]—see Benson *et al.* 2000, and the Saturn Information System, Dräger—see Driscoll *et al.* 2007), but some can be far from ideal, and relatively unhelpful in facilitating anaesthesia-related activities, or even generating good quality records. These latter failings largely account for the poor take-up of commercial systems by anaesthetistsin the UK. That said, improvements are of course being made all the time.

Computerisation also offers a significant research benefit. For example, in a study by

[47] Xenon5; © Nickalls RWD, Dales S and Nice AK (1996–2011) —see Figure 9.5, (page 151) and Figure **??** (page **??**).

[48] IMESO, GmbH, Huttenberg, Germany.

Müller *et al.* (2002) anaesthetists were able to search the database of their automated anaesthesia record-keeper and establish useful risk factors predictive of subsequent inotropic support requirement following cardio-pulmonary bypass. Driscoll *et al.* (2007) used AIMS data to establish underdosage as the cause of awareness in three patients.

Databases

Extracting data from big databases requires a good data dictionary (Sanderson and Monk 2003) as, for example, the currently well advanced SNOMED Clinical Terms program (SNOMED-CT),[49] which is a dynamic health care terminology infrastructure being developed as part of the NHS National Program for Information Technology (NPfIT). A demonstration program can be accessed from the SNOMED-CT home page.

Another NPfIT dictionary database of interest to anaesthetists is the Dictionary of Medicines and Devices (DM+d).[50] This consists of a number of coordinated XML-encoded pharmaceutical databases, which also incorporate the associated SNOMED encoding. Of particular interest to anaesthetists is the Virtual Therapeutic Moiety (VTM) database of approximately 2000 official drug names which are to be used henceforth in all European computer interactions relating to drugs. This list is updated frequently and can be downloaded from the website (password required). This useful list was incorporated into the author's experimental anaesthesia workstation used in the CHN thoracic theatres.

The future

The future holds the exciting prospect of developing sophisticated (and possibly Open Source) anaesthesia workstations giving anaesthetists access to good data displays and trends, sophisticated alarms (smart-alarms), real-time predictive modelling for drugs and physiological parameters, information management and decision-support systems (Sanderson, Watson and Russell 2005; Tarassenko, Hann and Young 2006, Berkenstadt *et al.* 2006). A good overview of what might be possible (in a USA office setting) was presented by Gage (2002). Since 2010 the NHS has been eagerly embracing the Open Source domain—this can only be a good sign for anaesthetists.

9.8.3 References

- Adams AP (1996). A revised anaesthetic record set. *Royal College of Anaesthetists' Newsletter* 27 (1996); 8–9.
- Beecher HK (1940). The first anesthesia records (Codman, Cushing). *Surg. Gynecol. Obstet.*, 71, 689–693.
- Benson M, Junger A, Fuchs C, Quinzio L, Bottger S and Hemplemann G (2000). Use of an anesthesia information management system (AIMS) to evaluate physiologic

[49] http://www.snomed.org/snomedct/
[50] http://www.dmd.nhs.uk/

effects of hypnotic agents used to induce anesthesia. *J. Clin. Monit. Comput.*; 16, 183–190.

- Berkenstadt H, Yusim Y, Katznelson R, Ziv A, Livingstone D and Perel A (2006). A novel point-of-care information system reduces anaesthesiologists' errors while managing case scenarios. *European Journal of Anaesthesiology*, 23, 239–250.
- Byrne AJ, Sellen AJ and Jones JG (1998). Errors on [handwritten] anaesthetic record charts as a measure of anaesthetic performance during simulated critical incidents. *Br. J. Anaesth.*;80, 58–62.
- Cushing HW (1902). On the avoidance of shock in major amputation by cocainization of large nerve trunks preliminary to their division. With observations on blood pressure changes in surgical cases. *Annals of Surgery*, 36, 321–345. [from Hirsch & Smith (1986)]
- Cushing HW (1903). On routine determinations of arterial tension in operating rooms and clinic. *Boston Med. Surg. Journal*, 148, 250–256. [from Hirsch & Smith (1986). Reproduced in 'Classical File', *Survey of Anesthesiology* (1960); 4, 419]
- Driscoll WD, Columbia MA and Peterfreund RA (2007). An observational study of anesthesia record completeness using an Anaesthesia Information Management System. *Anesthesia and Analgesia*; 104, 1454–1461.
- Ellis RH (1995). *The Casebooks of Dr John Snow*. (Wellcome Institute for the History of Medicine); p. 22, p. 30.
- Fulton JF (1946). Harvey Cushing—a biography. (Charles C Thomas, Springfield, IL, USA).
- Gage JS (2002). Anesthesia Informations Management Systems (AIMS). *ASA Newsletter*, June 2002. (http://www.asahq.org/Newsletters/2002/6_02/gage.html).
- Hallén B (1990). The value of anaesthetic records for morbidity and mortality studies. In: Kenny GNC [Ed.], Automated Anaesthetic Records; *Baillière's Clinical Anaesthesiology*; 4 (June), pp. 7–16.
- Hirsch NP and Smith GB (1986). Harvey Cushing: his contribution to anesthesia. *Anesthesia and Analgesia*; 65, 288–293.
- Kennedy PJ, Feingold A, Wierner EL and Hosek RS (1976). Analysis for tasks and human factors in anaesthesia for coronary-artery bypass. *Anesthesia and Analgesia*; 55, 374–377.
- Kenny GNC [Ed.] (1990). Automated anaesthesia records. *Bailliere's Clinical Anaesthesiology*; 4 (June).

- Kitz RJ (2006). World's first computer-controlled anesthesia machine donated to WLM[51] *ASA Newsletter*, 70 (September). (http://www.asahq.org/Newsletters/2006/09-06/kitz09_06.html).
- Kofke WA and Nadkarni VM [Eds.] (2007). New vistas in patient safety and simulation. *Anesthesiology Clinics*; 25 (June), 209–390 (Elsevier, Inc)

  [chapters: Anesthesiology national CME program and ASA activities in simulation / Does simulation improve patient safety?: self-efficacy, competence, operational performance, and patient safety / Simulation applications for human factors and systems evaluation / Credentialing and certifying with simulation / Statewide simulation systems: the next step for anesthesiology? / Crew resource management and team training / Simulation: translation to improved team performance / Virtual worlds and team training / Virtual reality simulations / Procedural simulation / Debriefing with good judgment: combining rigorous feedback with genuine inquiry / Integration of standardized patients into simulation]
- Lack JA, Stewart-Taylor M and Tecklenburg A (1994). An anaesthesia minimum data set and report format. *Br. J. Anaesth.*;73, 256–260.
- Leedal JM and Smith AF (2005). Methodological approaches to anaesthetists' workload in the operating theatre. *Br. J. Anaesth.*; 94, 702–709.
- Meyer-Bender A, Spitz R, Pollwein B (2010). The anaesthetic report: custom-made printouts made from anaesthesia-information-management-systems using extensible stylesheet language transformation. *Journal of Clinical Monitoring and Computing*; 24, 51-60.
- Middleton H (1957). *Proc. Roy. Soc. Med.*; 50, 888. [from Middleton (1958a)]
- Middleton H (1958a). A cumulative anaesthesia record system. *Anaesthesia*; 13, 337–340.
- Middleton H (1958b). *Brit. Med. Bull.*; 14, 42. [from Middleton 1958a]
- Mounier CCR (1855). *Acad. Sci. Paris*; 40, 530. [from Rushman, Davies and Atkinson (1996)]
- Müller M, Junger A, Bräu M, Kwapisz MM, Schindler E, Akintürk, Benson M and Hempelmann G (2002). Incidence and risk calculation of inotropic support in patients undergoing cardiac surgery with cardiopulmonary bypass using an automated anaesthesia record-keeping system. *Br. J. Anaesth.*; 89, 398–404.
- Nickalls RWD (1998). TEX in the operating theatre: an anaesthesia application. *TUG*BOAT; 19, 239–241. http://www.tug.org/TUGboat/Articles/tb19-3/tb60nick.pdf

[51] Wood Library-Museum of Anesthesiology.

- Nickalls RWD (1999). mathsPIC: a filter program for use with PiCTeX. *EuroTeX'99 Proceedings* 1999; p 192–210. http://www.uni-giessen.de/~g029/eurotex99/nickalls.pdf
- Nickalls RWD (2000). mathsPIC 2·1 http://www.tex.ac.uk/tex-archive/graphics/mathspic/
- Nickalls RWD (2003). Age-related iso-MAC charts for download. http://www.nickalls.org/dick/papers/rwdnPapers.html#anes-general
- Nickalls RWD and Mahajan RP (2010). Awareness and anaesthesia: think dose, think data. *Br. J. Anaesth.*; 104, 1–2. [Editorial] http://www.doi.dx/10.1093/bja/aep360
- Nickalls RWD and Mapleson WW (2003). Age-related iso-MAC charts for isoflurane, sevoflurane and desflurane in man. *Br. J. Anaesth.*; 91, 170–174. http://www.doi.dx/10.1093/bja/aeg132
- Nickalls, Dales SD and Nice A (2010) A Linux-based anaesthesia workstation ESCTAIC-2010 conference (Amsterdam; October 6-10, 2010)
- Nickalls, RWD and Ramasubramanian R (1995). *Interfacing the IBM-PC to medical equipment: the art of serial communication.* ISBN 0-521-46280-0; 402 pp. (Cambridge University Press).
- Noseworthy M (1937). *St. Thomas's Hospital Reports (London)*; 2, 54. [from Rushman, Davies and Atkinson (1996)]
- Noseworthy M (1943). *Br. J. Anaesth.*; 18, p. 160). [from Oldham (1963); Middleton (1958)]
- Noseworthy M (1945). *Anesthesia and Analgesia*; 24, 221. [from Rushman, Davies and Atkinson (1996)]
- Noseworthy M (1953). *Anaesthesia*; 8, 43. [from Noseworthy (1963)]
- Noseworthy M (1963). Anaesthetic record card. *Anaesthesia*; 18, 209–212.
- Oldham KW (1963). Anaesthetic and operation records. *Anaesthesia*; 18, 213–216.
- Rushman GB, Davies NJH and Atkinson RS (1996). *A short history of anaesthesia: the first 150 years.* (Butterworth-Heinemann, Oxford, UK). [see Chapter 14; Monitoring, pp. 154–161]
- Sanderson IC and Monk TG (2003). Standard anesthesia terminologies: how can we avoid wasting the data we collect? *ASA Newsletter*; 67, November. http://www.asahq.org/Newsletters/2003/11_03/sanderson.html [The November ASA Newsletter was a special issue on "Performance and outcome measures"]

- Sanderson PM, Watson MO and Russell WJ (2005). Advanced patient monitoring displays: tools for continuous informing. *Anesthesia and Analgesia*; 101, 161–168.
- Smith A (1997). New college guidelines for anaesthesia records: how do current forms measure up? *Royal College of Anaesthetists' Newsletter* 36 (1997); 3–6.
- Syropoulos A and Nickalls RWD (2000). A perl port of the mathsPIC graphics package. *TUGboat*; 21: 292–7. http://www.tug.org/TUGboat/Articles/tb21-3/tb68syro.pdf
- Tackley R (2006). Integrating anaesthesia and intensive care into the National Care Record. *Br. J. Anaesth.*; 97, 69–76.
- Tarassenko L, Hann A and Young D (2006). Integrated monitoring and analysis for early warning of patient deterioration. *Br. J. Anaesth.*; 97, 64–68.
- Thrush DN (1992a). Are automated anesthesia records better? *J. Clin. Anesth.*; 4, 386–389.
- Thrush DN (1992b). Automated anesthesia records and anesthetics incidents. *J. Clin. Monit.*; 8, 59–61.
- Thys DM (2001). The role of information systems in anesthesia. (http://www.apsf.org/resource_center/newsletter/2001/summer/03Infosys.htm).
- Waters RM (1936). The teaching value of records. *Journal of the Indiana Medical Association*; 29, 110. [from Hallén 1990]
- Waters RM (1942). The evolution of anaesthesia. *Proceedings of the Mayo Clinic*; 17, 40. [from Hallén 1990]
- Weinger MB, Herndon OW and Gaba DM (1997). The effect of electronic record keeping and transesophageal echocardiography on task distribution, workload, and vigilance during cardiac anesthesia. *Anesthesiology*; 87, 144-155.
- Westhorpe R (1989). McKesson 'Nargraf' anaesthetic record. *Anaesthesia and Intensive Care*; 17, 250.
- Wong DH, Gallegos Y, Weinger MB, Clack S, Slagle J and Anderson CT (2003). Changes in intensive care unit nurse task activity after installation of a third-generation intensive care unit information system. *Critical Care Medicine*; 31, 2488–2494.