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Design solutions for medical technology: Charles Drew's profound hypothermia apparatus for cardiac surgery

The modern medical specialty of open-heart surgery had its origins in the 1950s. The development of apparatus to take over the function of the patient's heart and lungs during surgery played a central role, and much of the early work was done in US medical centres. John Gibbon of Philadelphia was the first to operate successfully using a heart–lung machine, in 1953.[1] The Mayo Clinic subsequently modified Gibbon's machine for their own open-heart programme. At Minnesota University during 1954–55, C. Walton Lillehei championed his cross-circulation technique, in which a patient's relative took the place of a heart–lung machine. Lillehei later devised and used a heart–lung machine in collaboration with Richard DeWall.[2]

By 1960, these and other surgeons had established, if not standard procedures, then at least the feasibility of open-heart surgery using cardiopulmonary bypass and, potentially curative of otherwise fatal conditions such as congenital heart defects in children, open-heart surgery slowly came into routine use. In London, several teaching hospitals began programmes in the late 1950s or early 1960s. The adoption of new technology was an integral part of open-heart surgery in the early years and, in Britain, major decisions over heart–lung machines preoccupied many surgeons: should an expensive purchase be made from the USA, or should a "home-made" version be devised in the hospital workshops? Or indeed, as will be presented in this case study, should an altogether alternative form of technology be pursued?

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The raison d'être of museums is, of course, their artefacts, and the "black boxes" of modern technology cause curators much angst, offering, at first sight, rather less potential for analysis than their more ornate and less opaque precursors. However, recent work in the history and sociology of technology offers much potential for the analysis and display of these modern artefacts. In this paper, both contingent factors and the specific culture of British operative surgery during a transitional period will be shown to have played key roles in deciding why a piece of surgical technology finally took the form it did.

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Charles Drew's apparatus for his technique of open-heart surgery under profound hypothermia was developed around about 1960. The apparatus has been in the Science Museum's collections since 1987, and it went on permanent display in the *Health Matters* gallery in 1994. One of the principal intentions in that gallery was to make the selection of objects for display, and the display treatment itself, more in line with new perspectives in the history of medicine and of technology. With these concerns uppermost, it appeared to be a promising case study. There were, for example, extensive accounts of the design process, with striking evidence of industrial involvement and transfer of skills and technology from outside medicine. At an early stage, there had been much "ad hocery" and improvisation in the apparatus used. After initial acclaim, the technique had apparently been abandoned within a few years by most surgeons, but was still advocated by its inventor, so there was the promise of controversy. Subsequently, the method had been assessed as "not mainstream" – that is, not on the rather direct path that some historians maintain can be traced for the "development" of open-heart surgery.[3]

The major design work on Drew's apparatus was carried out between 1959 and 1961 at the Westminster Hospital, London, where Charles Drew (1916–87) was a thoracic surgeon.[4] By his own account, he was seeking a simpler way of doing open-heart surgery than using a heart–lung machine. In particular, it frustrated him that, when using a heart–lung machine, "the perfect oxygenator" (that is, the patient's own lungs) "lay fallow in the chest."[5] Heart–lung machines were, of course, designed to pump and oxygenate the patient's blood outside the body, thus bypassing both heart and lungs. Surgeons reported several problems with the models then available. Most of these were still unique "one-off" versions, devised by individual medical men in collaboration either with companies, such as IBM, General Motors or AGA, or with hospital physicists or engineering departments.[6]

The problems that surgeons in the 1950s most frequently associated with heart–lung machines were first, that they required large priming volumes of stored blood (which was detrimental to the patient's body chemistry and clotting functions) and second, that the artificial-lung component damaged the blood cells as they passed through it. However, less specific criticisms make it clear that, to many surgeons in the mid 1950s, heart–lung machines seemed just "complicated," and "difficult to run."[7]

Drew himself had tried a Lillehei–DeWall type heart–lung machine in 1955–56, during which period he experienced "difficulties, disappointments and the set-backs well known to everyone who has undertaken this type of work."[8]

Seeking an alternative to the use of a heart–lung machine, Drew developed the technique he called "profound hypothermia."[9] This involved cooling the patient down to about 15°C, at which point the heart stopped beating and the patient was, to all intents and purposes, clinically dead. Heart surgery could then be performed (with a self-imposed one-hour time limit) and the patient rewarmed, whereupon the heart usually restarted, either spontaneously or with electrical stimulation. In this way, Drew obviated the need for artificial oxygenation of the blood – this took place in the patient's own lungs, which could be artificially ventilated until, at low temperatures, they were not required. Since the 1930s, hypothermia had been the subject of considerable research, first as a potential cancer therapy, and then in relation to the survival of shipwrecks in the Second World War. Findings suggested that, in controlled cooling to low temperatures, the brain and heart might survive undamaged for limited periods with little or no oxygen.[10]

Drew did, of course, need the "pump" component of heart–lung machines for two purposes. First, he needed to be able to maintain the circulation of the blood artificially, in case the heart stopped during the cooling process but before sufficiently low temperatures had been reached (the usual cause of death in accidental exposure to cold). Second, in order to reach such low temperatures, he cooled the patient, not directly, but by cooling their blood in a heat exchanger as it circulated outside the body and then pumping the cooled blood back into them. In early case series, Drew's team used a makeshift heat exchanger for the blood that comprised steel tubes placed in a length of roof guttering, through which ran hot or cold water.[11] Subsequently, the much more sophisticated apparatus that is the subject of this paper was devised. It incorporated two "roller" blood pumps of a type used widely in extracorporeal bypass, but with an innovative annular heat exchanger mounted on trunnions and supplied with iced and hot water from a separate unit.

In the early 1960s, Drew's success rates with this apparatus were comparable to those of any of the small number of other surgeons doing open-heart work. (The patients were often children, open-heart surgery at that period being dominated by the repair of simple or moderately complex congenital heart defects sometimes known as "holes in the heart." Problems with the valves of the heart, such as those arising as long-term sequelae of rheumatic fever, were considered to be technically much more difficult.) In particular, Drew's success rates in correcting Fallot's tetralogy, a complex fourfold congenital abnormality, were better than those of other surgeons, with a mortality rate of 15%.[12]

However, if this apparatus was an initial success for Drew, in other ways it was a failure. It seems probable that only three more machines of this kind were ever produced, one for the other London hospital at which Drew performed open-heart surgery, St George's.[13] By the late 1960s, the only hospitals using profound hypothermia were the two at which Drew himself operated (the Westminster and St George's). An isolated "objective clinical trial" of the method, reviewing results at Bristol Royal Infirmary from 1960 to 1967, was published in 1968.[14]

Participants in heart surgery at that time recalled some apparently obvious and fairly unanimous reasons for the the demise of the technique.[15] First, it was said that the one-hour operating time limit grew increasingly irksome: as the repair of more complex defects involving the heart valves began to be attempted, even the faster surgeons found that one hour was not long enough to complete the operative repair; and second, it was recalled that the performance of heart–lung machines improved considerably during the 1960s. When asked why Drew persisted in using the technique of profound hypothermia for the rest of his career, to the extent that, by the mid 1970s, physicians were reluctant to refer patients to him for heart surgery because of it, several of those interviewed considered that the reason was simply that he had invented the technique, and was therefore wedded to it.

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An *idée fixe* is perhaps one of the least appealing explanations for sociologically minded historians. Furthermore, the reasons for abandoning profound hypothermia given by cardiac surgeons – admittedly through the "retrospectoscope" – seemed so convincing. Could it be that this artefact, which had seemed so promising a candidate from the perspective of what might be called the "new" history of technology, was in fact an "open-and-shut" case? It seemed that some "problematisation" of the issues involved might prove fruitful. A number of other questions could be pursued, in particular those raised by the form of the apparatus itself, which might further illuminate issues to do with the success of the technique, the machine, or both. Why was it built as it was? Why did it look as it did? Drew's apparatus actually looked very *unlike* other medical equipment devised at this time (*see* Figure 1). The notion that form follows function has come under attack by historians of technology in recent years.[16] Might this machine have been built differently, looked different? First of all, did it have to be so big? It was very big – huge, given the size of the average operating theatre.

The design process is relatively well documented. It did not, as one might have expected at that time, involve a hospital physics or engineering department. The Westminster, Drew's own hospital, had a particularly active and innovative medical scientist in Percy Cliffe, who was well known for devising new apparatus and became head of the Department of Clinical Measurement there in 1959.[17] However Drew had it seems temporarily fallen out with Cliffe.[18] When he first began to think seriously of how to cool down his patients, Drew went, not to Cliffe, but to a copy of a standard engineering textbook – *An Introduction to Heat Transfer* by Fishenden and Saunders.[19] Finding it difficult reading, he consulted the senior author, Owen Saunders, then Professor of Mechanical Engineering at Imperial College, London.[20] Saunders put Drew in touch with a refrigeration engineer from the APV Company whom he had supervised for a Master's thesis on the cooling of non-Newtonian fluids. This led to an extremely close collaboration with the engineer in question, David Shore, and with APV, process engineers to the food industry working especially with brewing, and dairy and ice-cream plants.[21]

Figure 1 (left). The heat exchanger, blood pumps and control unit of the profound hypothermia apparatus designed for Charles Drew by the APV Company. The inset shows the internal construction of the heat exchanger.

Figure 2 (right). The heating and cooling unit of APV designed apparatus, which was sometimes placed outside the operating theatre.

Shore eventually published full accounts of the design of the machine in a paper to the Institution of Mechanical Engineers and in the *Journal of Refrigeration.*[22] Both papers make reference to the choice of controls used on the apparatus. In the *Journal of Refrigeration,* Shore wrote that "The visual aid offered by pneumatic control, together with its simplicity, was considered by our design team to outweigh other merits of the electric or electronic control systems."[23] In his paper to the Institution of Mechanical Engineers, he stated that pneumatic controls were considered "more reliable than electric or electronic equipment."[24]

Here was a clear indication of a choice being made concerning the form of the machine – and the first suggestion that it might have been made differently. Further inquiry into this issue of the controls leads one to speculate about the reasons given for the use of pneumatic controls. A reluctance to use electronic controls was apparently widespread amongst mechanical engineers at this period. For example, the guidance notes for sales representatives of the Cambridge Scientific Instrument Company in the 1950s stated: "this craze for the use of electronic circuits as applied to measuring and recording instruments is often ill-founded and may be pressed to disadvantage for the user ... electronics is a great and potent means of furthering instrumentation ... use it if you must, but never if you need not."[25] Of course, Shore was not only a mechanical engineer but his company, APV, specialised in process engineering. Several authors have stressed how pneumatic controls were traditionally favoured in process control.[26] Their use goes some way towards explaining the size and general ungainliness of Drew's equipment: to operate the controls required air lines and a compressor, or an air bottle of 48 cubic feet capacity that would last for two operations.[27] An even larger component, however, was the heating and cooling unit for the supply of iced and hot water – so large that it was, in practice, usually accommodated outside the operating theatre, sometimes in a corridor or the anaesthetic room (*see* Figure 2). The design remit that Drew gave to Shore was to devise a heat exchanger capable of cooling a body weighing 150 pounds from 37°C to a mean of 15°C in half an hour, with an extracorporeal blood flow of 3 litres per minute, the blood temperature never rising above 40°C nor falling below 4°C.[28] Shore worked meticulously to these and other specifications, ever aware of the need for the apparatus to "fail to safety," and that he had a patient's life to consider, rather than the workings of an ice-cream plant. He devised an extremely sensitive annular form of heat exchanger. To secure precise control of the temperature of the water supplied to it, he provided a refrigeration unit with ice bank and heating element, and a safety valve that ensured the water simply recirculated in the event of a fault in the thermoregulation. This added considerably to the bulk and complexity of the equipment.

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Having thus begun to consider how this apparatus might have been built differently, it seems logical to determine what apparatus was used by other teams practising profound hypothermia. It seems clear that the success of Drew's apparatus is a question rather separate from the success of the technique of profound hypothermia itself. Several leading cardiac centres *did* use profound hypothermia, with enthusiasm and with good success rates, for a period of about five years, when it was seen as a genuine alternative to heart–lung machines and thought to have considerable potential for the future.[29] It was the method of choice, for example, at St Bartholomew's Hospital from 1961 to 1965.[30] Clearly, the technique of profound hypothermia had a separate life from the apparatus designed by APV. What then, were the other teams using?

In London, at St Bartholomew's and also at King's College Hospital, open-heart surgery under profound hypothermia was performed with a piece of equipment devised within 18 months of Drew's, but in quite striking contrast to it.[31] Smaller and much less cumbersome, it was made by a company called New Electronic Products (NEP); not surprisingly, therefore, it had electronic controls. Other features resulted in a reduction

Figure 3. NEP apparatus used for profound hypothermia at St Bartholomew's Hospital, from the technical manual.

in overall size. The heat exchanger was much smaller and simpler, and merely clamped to a pole, whereas in the APV machine the heat exchanger was mounted on trunnions so that it could be up-ended to allow air to escape. There was a separate refrigeration and heating unit, but this did not incorporate an ice bank, so was smaller than that with the APV machine; however, some surgeons did not go to the trouble of using it, preferring instead the water supply from an ordinary sink, and some ice.[32]

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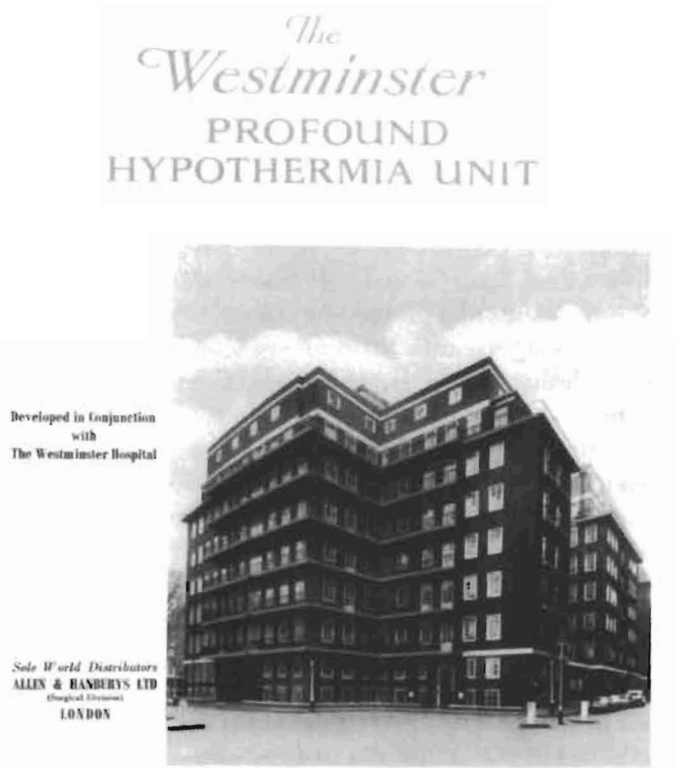
In many ways, the whole ethos of these two machines, designed for the same purpose within 18 months of each other, was entirely different. The machine that Shore designed at APV is redolent of his background in refrigeration and process engineering. It was large: space was rarely a problem in processing industries. The control element was immensely precise. In other details, instrumentation familiar to process control was chosen – the Taylor Fullscope recorder controller, for example, on which continuous circular records of inflow and outflow water temperature were plotted. This was unknown in medical instrumentation of the period. The NEP machine had a simple dial indicator instead.

The design problem was presented in a way that was very familiar to APV – an individual customer presenting them with a problem for which they designed a one-off solution. (APV had a strong problem-solving tradition: in later years, they solved the problem of the Cadbury's Creme Egg.[33]) What APV did not design were mass produced products; NEP, however, explicitly did so. They were a small company, founded in 1947. Some of their business came from the Royal Aircraft Establishment at Farnborough, for whom they designed miniature galvanometers; physiological recording equipment in general was an important part of their output.[34] Their "ethos," judging from surviving advertising material, was one of size reduction, self-containment and modular construction, all based on electronics.[35] Seen through half-closed eyes, as it were, their apparatus looks more "modern" than that of APV, perhaps partly because of its cream-painted sheet cladding. APV's use of stainless-steel and bent-tube construction gave their machine a similarity, not only to the dairy and brewing equipment they were used to producing, but to a style of hospital furniture that had been predominant since the years between the First and Second World Wars. Although there is no direct evidence of the involvement of industrial designers in the development of the NEP machine, it is noteworthy that their parent company, Honeywell, was one of the earliest to employ such specialists on a permanent basis.[36] One might speculate how much factors such as these, rather than those actually recalled by surgeons, influenced the limited success of the APV machine. As a study of the acquisition of computed tomography (CT) scanners by US radiologists in the 1970s has shown, the reasons that decision makers recall as underlying their acquisition of new technology – such as documented increased efficiency – frequently do not stand up to closer scrutiny.[37] Less often recalled reasons for acquisition may include, for example, institutional prestige, or the persuasive power of marketing techniques.

NEP marketed their machine themselves, but APV, once satisfied that their apparatus was working satisfactorily, passed this function to the company Allen & Hanburys, apparently considering that it was too far from their normal line of business to undertake the marketing effectively themselves.[38] The choice was perhaps not fortuitous. Allen & Hanburys were an old-established firm, founded in 1715, who made proprietary medicines, surgical instruments and hospital furniture;[39] they had no tradition of making or selling scientific instruments. Comparison of their advertising material with that of NEP is interesting. In the brochure that Allen & Hanburys produced to promote the APV apparatus, the front cover is devoted to a large, architectural photograph of the Westminster Hospital. The imposing nature of the building is accentuated by the low camera angle, invoking all the connotations of tradition and authority associated with a London teaching hospital (*see* Figure 4). NEP's advertising looked quite different. Promotional material for their profound hypothermia apparatus has not been traced, but leaflets produced to advertise other pieces of medical equipment at the same period have been preserved (*see* Figure 5).[40] They feature brightly coloured, "contemporary" artwork, rather than black-and-white photography; the stylised image of a hand brings connotations of ease of use and compactness; the company's affiliation to Honeywell Controls, suppliers of instrumentation to the US space programme, is prominently mentioned. In contrast, Allen & Hanburys chose to emphasise their product's association with an old and venerated medical institution. By deciding to call it the "Westminster Profound Hypothermia Apparatus" they had almost, if not quite, reverted to a tradition predominant in the medical supply trade throughout the nineteenth and early twentieth centuries – that of eponymous naming. They did not go so far as to call it the "Drew apparatus," but they did the next best thing, naming it after his *alma mater*. This tradition was dying elsewhere in the rapidly expanding field of medical equipment. It is perhaps not difficult to see how to some the NEP machine, with its connotations of scientific precision, greater air of "modernity," small size and possibly industrially designed shape, might have proved more attractive than APV's larger machine which was marketed on authority and tradition.

These contrasts in advertising practice, and in the two machines themselves, can, I believe, be linked to considerable change in surgical practice after the Second World War. In the rhetoric of the newer surgical specialties of the 1950s and 1960s, there are some words that occur repeatedly. One is the word "new" itself, and another is the word "scientific;" but there is a third word – "teamwork" – which it is interesting



The Westminster
PROFOUND
HYPOTHERMIA UNIT

Developed in Conjunction
with
The Westminster Hospital

Sole World Distributors
ALLEN & HANBURYS LTD
(Surgical Division)
LONDON

Figure 4. Front cover of Allen & Hanburys advertising brochure for Drew's profound hypothermia apparatus, showing the Westminster Hospital.

to explore in relation to Drew's apparatus. Nowhere was use of this word more prominent than in the area of open-heart surgery. In this emergent specialty, existing groups, such as anaesthetists, took on far more central roles. New groups came into being, especially of paramedics occupying key positions, for example as pump technicians. New degrees of liaison and interdependency were set up, not only inside the operating theatre, but outside it too – in postoperative intensive care, for example – and with cardiac physicians, on whom surgeons were dependent for the preoperative assessment of patients and, indeed, for referring patients to them in the first place. As one leading heart surgeon of the period recalled, surgeons had to make the transition from being "captain of the ship" to being "chairman of the board."[41] Not all of them made it; it seems possible that Charles Drew himself failed to make it. He was recalled by many as autocratic in theatre. He did not hesitate to curse his junior staff, but was quick to make amends, and inspired fierce loyalty: one doctor who had worked for him as a house surgeon referred to himself as being one of a group known as "Drew's boys," and recalled how some of them would pretend not to hear the consultant anaesthetist's interjections during an operation, taking notice only of Drew himself – hardly a situation conducive to team-building.[42] It seems very likely that Drew was a captain of the ship and not a chairman of the board. In view of this, it is perhaps not surprising that he devised his machine largely independently of colleagues in other medical specialties – specialties that were to become essential to successful open-heart surgery. As mentioned above, he bypassed Percy Cliffe, the inventive medical scientist at the Westminster, a "natural" for Drew's project if ever there was one, because he had apparently fallen out with him. Drew the surgeon worked with Shore the engineer to produce a machine that satisfied the surgeon's and the engineer's criteria. The technique of profound hypothermia itself, alone of any other used in open-heart surgery of the period or since, produced a still, bloodless heart – the perfect operating conditions for the surgeon. In engineering terms, Shore's heat exchanger was more sophisticated than any other used in open-heart surgery in Britain or abroad.[43]

Figure 5. Example of NEP advertising literature from the early 1960s. The stylised image of a hand, in black on a bright red background, had a contemporary feel. It brought connotations of ease of use and compactness.

The concerns of other workers, however, were not always addressed. Two consultants referred, independently, their concerns over Drew's apparatus. One was an anaesthetist, who recalled that the low priming volume – a specific request of Drew's, to avoid the problems of stored blood meant that, if there were any obstruction in the blood circuits, the reservoirs would run dry in seconds, pumping air into the patient's circulation, with potentially fatal results.[44] This machine, which produced almost perfect operating conditions for the surgeon, required nerves of steel in the anaesthetist or pump technician who ran it. For other groups, such as the theatre staff who set up and dismantled it, taking several hours in all, the machine also had disadvantages.

It might not be impossible to write an account of these machines comparable to that produced by Pinch and Bijker for the bicycle – showing how the relative strengths of various interest groups affected the ultimate design.[45] In contrast to Drew's machine, the NEP apparatus was designed by a trio of consultant surgeon, anaesthetist and physiologist.[46] Several design features demonstrated concern for the various team members' jobs, not just the surgeon's. Photosensitive safety devices were fitted, for example, to give audible alarms if the reservoirs were in danger of running dry. A special feature was made of the fact that the machine operator could sit facing the operation, which apparently was not possible with Drew's machine. It was much simpler to assemble, take apart and sterilise. It probably cost less, too. It is possible that Allen & Hanburys might have sold the APV apparatus almost at cost, in order to launch a new product of this kind. Even so, the price was likely to have been more than £1000.[47] Charles Drew himself was largely freed from financial constraints in his research, by an endowment from a grateful and wealthy benefactor.[48]

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It is possible to see the Westminster apparatus for profound hypothermia as an embodiment of Charles Drew's concerns and priorities and perhaps somewhat autocratic tendencies, his preferred ways of working, and the prevailing institutional and financial circumstances that allowed these a fairly free rein. Further evidence for this interpretation comes from the typescript of a lecture that Drew gave in Tokyo in 1968. His collaboration with David Shore and APV continued more or less throughout the 1960s, and by this time Drew had made several modifications to his original extracorporeal circuit, most notably in substituting a single reservoir for separate ones in the right and left circuits. By 1968, he was considering discarding reservoirs entirely, replacing them with heat exchangers, using a shunt between the two venous lines to equalize flow through the pumps, using the same shunt line for the giving of blood, and at the same time removing air from the lines to the heart immediately after cannulation. He had very particular reasons for doing this. "Such a circuit," Drew wrote, "could be placed at the head of the table and manipulated by the surgeon, for this reason: during cooling the surgeon is not concerned with the open heart and can therefore control the extracorporeal circulation; during open heart surgery, the extracorporeal circulation is no longer used. When he has finished his manipulations in the heart, he can resume control of the extracorporeal circulation."[49] Here, indeed, is clear evidence of Drew's wish to take responsibility for every aspect of open-heart surgery, rather than distribute functions among a team, and of how this might very literally be translated into the design of apparatus. Drew's former senior registrar, John Bailey, on being read this quote, exclaimed "Oh yes, it was one of Charles' greatest aims to get rid of the perfusionist!"[50]

This is yet more supporting evidence, it seems, for the claim by certain historians of technology that machines are not adequately described by a single overt function. Charles Drew's apparatus was intended to cool patients to very low temperatures, but, at least in later forms, it seems it was also intended, consciously or otherwise, to "get rid of the perfusionist." Likewise, success is not measured solely in terms of performance specifications. One retired woman cardiac surgeon recalled how much she liked profound hypothermia because it was "so neat and tidy."[51]

When it comes to form, of course, all engineering solutions are "borrowed," but looking at where from, and why, can provide surprising insights.

Notes

1. J. H. Gibbon, Jr, "Application of a Mechanical Heart and Lung Apparatus to Cardiac Surgery," in *Recent Advances in Cardiovascular Physiology and Surgery* (Minneapolis, 1953), pp. 107–13. For an account of Gibbon and his work, see A. Romaine-Davis, *John Gibbon and His Heart-Lung Machine* (Philadelphia, 1991).
2. C. W. Lillehei, R. L. Varco, M. Cohen et al., "The First Open Heart Repairs of Ventricular Septal Defect, Atrioventricular Communis, and Tetralogy of Fallot Using Extracorporeal Circulation by Cross-circulation: A Thirty Year Follow-up," *Annals of Thoracic Surgery* 41 (1986): 4–21.
3. See, for example, G. Clowes, Jr, "The Historical Development of the Surgical Treatment of Heart Disease," *Bulletin of the History of Medicine* 34 (1960): 29–51.
4. "Obituary, Mr Charles Drew," *The Times*, June 6, 1987.
5. Drew papers, undated typescript, Holme Lecture, given by Drew at University College Hospital Medical School, p. 2.
6. Gibbon, and later the Mayo Clinic, worked with IBM. General Motors built a heart–lung machine for F. D. Dodrill in Detroit. See Romaine-Davis (n. 1 above), p. 139.
7. D. C. Cooley, "Perspectives in Cardiac Surgery with Personal Reflections," *Surgical Clinics of North America* 58 (1978): 895–906.
8. C. E. Drew et al., "Experimental Approach to Visual Intracardiac Surgery, Using an Extracorporeal Circulation," *British Medical Journal* 2 (1957): 1323–29, and Drew (n. 5 above), p. 2.
9. C. E. Drew, G. Keen, and D. B. Benazon, "Profound Hypothermia," *The Lancet* 1 (1959): 745–47; C. E. Drew and I. M. Anderson, "Profound Hypothermia in Cardiac Surgery: Report of Three Cases," *The Lancet* 1 (1959): 748–50.
10. O. G. Edholm, "Hypothermia and the Effects of Cold: Introduction," *British Medical Bulletin* 17, no. 1 (1961): 1–4. The whole issue was devoted to this subject.

11. C. E. Drew, "Cardiac Surgery at the Westminster Hospital," *Broadway,* Westminster Medical School Journal (March 1966): 25–27.
12. For an analysis of Drew's results see T. B. Boulton and R. L. Hurt, "The Drew Technique of Profound Hypothermia for Cardiac Surgery in the 1960s," in *Technologies of Modern Medicine,* ed. G. M. Lawrence (London, 1994), pp. 25–39, 34.
13. A machine of this design was also in use at the Brook Hospital, London. It is possible that another was exported to France.
14. R. H. Belsey et al., "Profound Hypothermia in Cardiac Surgery," *Journal of Thoracic and Cardiovascular Surgery* 56, no. 4 (1968): 497–509.
15. Interview of J. Bailey by G. Lawrence, April 15, 1996; interview of M. Braimbridge by G. Lawrence, September 27, 1995; interview of M. Sturridge by G. Lawrence, November 2, 1995; interview of W. Williamson by G. Lawrence, July 12, 1995; and see Boulton and Hurt (n. 12 above), p. 36.
16. See, for example, S. Lubar, "Culture and Technological Design in the 19th Century Pin Industry: John Howe and the Howe Manufacturing Company," *Technology and Culture* 28 (1987): 253–82.
17. "Obituary, P. Cliffe," *British Medical Journal* 305 (1992): 1154.
18. Interview of W. Williamson (n. 15 above).
19. M. Fishenden and O. A. Saunders, *An Introduction to Heat Transfer* (Oxford, 1950).
20. Interview of D. Shore by G. Lawrence and T. Boon, July 13, 1993.
21. G. A. Dummett, *From Little Acorns: A History of the APV Company Ltd* (London, 1981).
22. D. T. Shore, "Heat Exchange in Profound Hypothermia: Heat Exchanger Design for Blood During External Circulation," *Proceedings of the Institution of Mechanical Engineers, Thermodynamics and Fluid Mechanics Group 9 Jan 1963* (1963); D. T. Shore, "Profound Hypothermia," *Journal of Refrigeration* (May/June 1961): 50–52.
23. Shore (n. 22 above), p. 51.
24. Ibid., p. 10.
25. Quoted in A. Anderson, "The Story of Cambridge Instruments," *New Scientist* 114 (June 11, 1987): 57–58, a review of M. J. G. Cattermole and A. F. Wolfe, *Horace Darwin's Shop: A History of the Cambridge Scientific Instrument Company, 1878–1968* (Bristol, 1987).
26. J. T. Stock, "Pneumatic Process Controllers: The Early History of Some Basic Components," *Transactions of the Newcomen Society* 56 (1984–85): 169–78.
27. Shore (n. 22 above), p. 11.
28. Ibid., p. 5.
29. D. G. Melrose wrote in 1961 that profound hypothermia was "inherently simple in equipment and sparing of blood ... a most interesting field and one which may alter our present concepts." D. G. Melrose, "Types of Heart-Lung Machines Used in Extra-Corporeal Circulation," *Postgraduate Medical Journal* 37 (1961): 639–45.
30. Boulton and Hurt (n. 12 above), p. 30. King's College and The Brook Hospitals also used the technique in the early 1960s.
31. R. L. Hurt, "Apparatus for Profound Hypothermia by the Drew Technique," *The Lancet* 1 (1962): 783.
32. Personal communication, R. Hurt, December 29, 1995.
33. Interview of Shore (n. 20 above). The problem was to keep the yellow "yolk" separate from the "white" in the fondant filling of the chocolate egg.
34. Interview of R. Schild by G. Lawrence, February 10, 1997.
35. NEP Ltd. Industrial catalogue 1961–62, Science Museum Library Trade Literature Collection.
36. G. Hart, "Design Management: An I. D. Service for Capital Goods," *Design* 187 (1964): 46–53.
37. S. R. Baker, "The Diffusion of High Technology Medical Innovation: The Computed Tomography Scanner Example," *Social Science and Medicine* 13, pt. D (1979): 155–62.
38. Interview of Shore (n. 20 above).
39. G. Tweedale, *At the Sign of the Plough: 275 Years of Allen & Hanburys and the British Pharmaceutical Industry, 1715–1990* (London, 1990). A merger with Glaxo took place in 1958, but "during the 1960s, Allen & Hanburys continued very much as an independent company," p. 195.
40. Trade Literature Collection, Science Museum Library.

41. Interview of M. Braimbridge (n. 15 above).
42. Interview of T. Gould by G. Lawrence, June 29, 1995.
43. I. W. Brown at Duke University devised a new blood heat exchanger for use with extracorporeal circulation with the Harrison Radiator Division of General Motors Corporation in 1958, although not for profound hypothermia. I. W. Brown et al., "An Efficient Blood Heat Exchanger for Use With Extracorporeal Circulation," *Surgery* 44 (1958): 372–77. It used the simpler multitube design, however, which Shore considered unsuitable. See Shore (n. 22 above), p. 7.
44. Interview of J. Gil-Rodriguez by G. Lawrence, January 18, 1996.
45. T. Pinch and W. Bijker, "The Social Construction of Facts and Artefacts: Or How the Sociology of Science and the Sociology of Technology Might Benefit Each Other," *Social Studies of Science* 14 (1984): 399–441.
46. R. L. Hurt, *The Lancet* 1 (1964): 1198.
47. Interview of R. Myer by G. Lawrence, May 24, 1996.
48. Interview of J. Bailey (n. 15 above).
49. Drew Papers, typescript, "P. H. Tokyo June '68," p. 17.
50. Interview of J. Bailey (n. 15 above).
51. Interview of B. Slesser by G. Lawrence, May 5, 1996.