Nuclear medicine and the electronics revolution

by R.A. Dudley*

In nuclear medicine, diagnosis and research are conducted with the aid of radionuclides. Such investigations were among the first applications of radionuclides and probably are the most common. The field has progressed rapidly since its beginning half a century ago, as a result of three types of developments: ingenious ideas (e.g. radioimmunoassay and computed reconstruction of radiation images, for which medical physicists won Nobel prizes in the 1970s); availability of more favourable radionuclides (e.g. ^{99m}Tc and ^{125}I, pioneered in the 1960s), and advances in electronics (in torrents throughout its history). Electronics has transformed almost all technologies, but the purpose of this article is to note its impact on nuclear medicine and especially on the Agency's programme in this area.

The impact of the electronics revolution on nuclear medicine is exemplified by the change in imaging instruments over the last 25 years. A suitable radionuclide that emits gamma rays is administered to the patient; it is then the task of the imaging device to determine from what point in the body the gamma rays emerge, and hence what pattern of distribution the radionuclide has assumed in the body. This pattern may reveal where a tumour is located, or what region of the lung is no longer being supplied with blood, or (if its changes with time are also monitored) whether the pumping cycle of the heart is normal.

The first automatic imaging device was the "rectilinear scanner", commercially available in the mid-1950s. A small scintillation detector (2.5 cm diameter sodium iodide crystal coupled to a photomultiplier tube) was suspended over the relevant area of the body, with a lead collimator in front to prevent radiation from reaching the detector except if directed nearly along its axis. The detector was mechanically moved slowly back and forth over the body so that it examined, in turn, all points in a rectangular area of interest. The electronic impulses generated by gamma rays incident upon the detector, if found to be of suitable amplitude, caused a pen attached to the detector to put dots on a piece of paper. At the end of the measurement the paper showed a scattering of dots representing, in 2 dimensions, the pattern of distribution of the radionuclide in the body. The representation was crude for many reasons – incomplete collimation, too few detected gamma rays to define the pattern, no information in the third dimension. However, it could be medically useful provided the pattern of distribution did not alter significantly during the course of the 15 to 30 minute measurement. The circuitry was simple – a few tens of vacuum tubes – and the functions also: pulse amplification, amplitude selection, and counting, plus power supplies.

In the early 1960s a new imaging device became available: the "gamma camera". After 20 years, and many improvements, it remains the dominant imaging instrument in developed countries, but is still outnumbered by rectilinear scanners in most developing countries. In the gamma camera the detector is still a sodium iodide crystal, but of larger diameter (now up to 50 cm), coupled to many photomultipliers, and stationary. Its collimator is also lead, pierced by many adjacent holes allowing each point on the detector face to "see" only that part of the body directly in front of it. As with the scanner, each gamma ray striking the detector generates an electrical pulse. Now, however, the electronic circuitry scrutinizes the pulse not only to determine if its amplitude is acceptable, but also to determine *where* the gamma ray struck the detector. In other words, the spatial pattern is decoded electronically, rather than by mechanical motion as in the scanner. Finally, the position is recorded – originally as a fleeting dot on a television screen but now more commonly on a map in an electronic memory. Electronic decoding of position brings many advantages. The whole organ (e.g. heart) is in the field of view at once, so that if a rapid succession of frames is recorded (e.g. one every 0.1 second), the time pattern as well as spatial pattern of tracer in the beating heart is obtained. When the camera is coupled to a computer the full picture can be processed electronically: the number of counts recorded in any sub-region of interest can be compared with those in any other, or with the same region in the previous frame; contour lines can be automatically deduced, and used to select subregions of interest. Originally electronic decoding of position also brought disadvantages: for example, imperfections in the detector resulted in spatial distortion of the image. However, it is just these sorts of problems which can be corrected by modern electronics: a map of the distortion can be stored, and used to correct the decoded position of each recorded gamma ray.

Finally, using other detector configurations and additional electronic computing, it has been possible since about 1975 to determine the 3-dimensional

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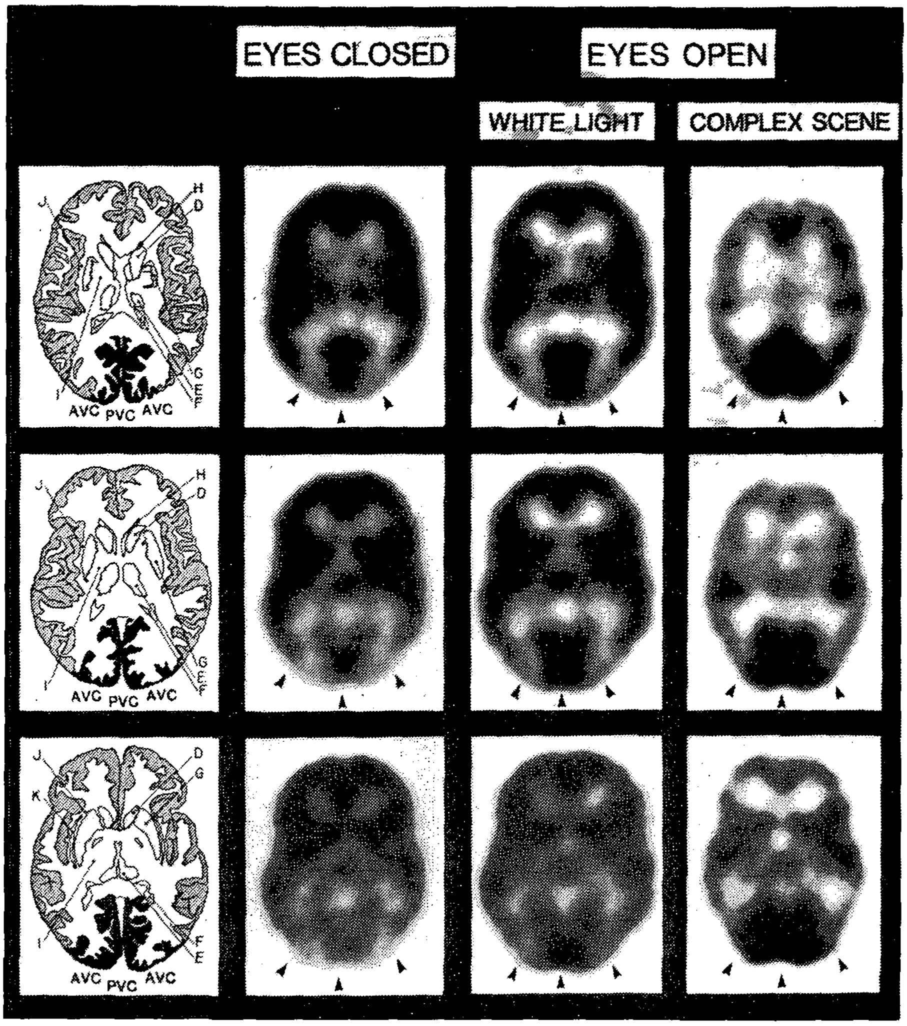


Sections through the human brain using the positron camera and showing changes within the visual cortex from eyes closed, to white-light stimulation, and to a complex visual scene of a park. [From M.E. Phelps et al., *Positron Computed Tomography*, in: Medical Radionuclide Imaging 1980, Vol.1, p. 199, IAEA, Vienna (1980)].

distribution of radionuclides in the body. (The strategy of computation was recognized in the award of the 1979 Nobel Prize in medicine; the key ideas had been available since early in the century, but they were neglected because their implementation was impractical without the computer.) If the radionuclide happens to emit positrons, especially favourable 3-dimensional images can be constructed. Perhaps today's ultimate in radionuclide imaging has been achieved by the "positron camera". With a spatial resolution of about 10 mm, a quantitative 3-dimensional image of the rate of glucose metabolism in various regions of the brain has been obtained, together with its dependence on what the subject is momentarily thinking about.

The imaging instruments just reviewed cover a broad range in technology. To set the scale, it may be noted that the current cost of scanner, computerized gamma camera, and positron camera are roughly US $25 000, US $200 000, and US $1 000 000, respectively.

Twenty-five years of revolution

The increased capability of imaging instruments has been made practical, above all, by advances in electronics. At the time of the first scanners, the basic electronic device was the vacuum tube – price a few dollars, dimensions a few cm, power consumption a few Watts, life expectancy a few months to a year or two. By the late 1950s these were replaced by transistors: for these, typically price was a few dollars, dimensions a few mm, power consumption a few tens of milliWatts, life expectancy years. In the early 1960s the discrete transistor was in turn replaced by "integrated circuits": several basic components – transistors, resistors, capacitors – were all formed together on a piece of silicon, already interconnected. No longer did each separate component have to be wired together by hand. This process of "integration" is still continuing unabated. Since 1960 the number of components in one integrated circuit has almost doubled every year, and is now of the order of a million. Remarkably, the cost, size, power consumption, and failure probability of entire integrated circuits have remained roughly the same as for the original transistors, implying that, per component transistor or per logical function, all of these have declined many thousand-fold since 1960. Speed of operation of the circuit has increased greatly.

Not only have circuits continuously become more compact, with the concomitant advantages just described; their logical organization has also been transformed, especially with the advent of the microprocessor in about 1970. A microprocessor corresponds to the central processing unit (CPU) of a computer – on a single silicon chip. While initially numerous additional integrated circuits (timer, memory, interface, etc.) had to be added to assemble a complete computer, by today the entire system can be fabricated on a single piece of silicon a few mm on a side.

Nuclear medicine instruments manufactured from these dramatically improved component parts reflect what the market, which is found in developed countries, has demanded. Three dominant trends may be noted. First, for any particular class of instrument, market forces have not brought constant performance at greatly reduced prices, but instead greatly improved performance at roughly constant prices. Of particular importance for developing countries has been the reduction in breakdown frequency. Second, technical developments periodically allow new classes of instruments to be introduced (e.g. scanner, gamma camera, positron camera); these may be offered at dramatically increased prices. Third, almost all instruments are now organized around microprocessors, so that the dominant feature of instrument design is no longer the hardware (devices) but rather the software (computer programs). While these trends are likely to be maintained for some time, the underlying revolution is likely to continue for years to come; users of instruments, and those who support them, must lay their plans in the face of sustained rapid change.

Nuclear medicine and the Agency's programme

How can developing countries, and the Agency as it responds to their needs, interact constructively with this electronics revolution and its impact on nuclear medicine? It is a little bit like trying to drink from a fire hose. Nevertheless, before becoming discouraged by the problems it is important to recognize that the dominant impact is very favourable; the hope is that it can be made even more favourable.

In 1975 the Medical Applications Section overtly identified instrumentation as one component of its programme. Among other activities, it undertook surveys of about 200 laboratories in Asia, Latin America, and Africa to find out what instruments were in use and, over a 6-month period, what maintenance problems arose and if and how they were solved. Each year under its technical co-operation and research contract programmes the Agency supplies several hundred thousand dollars' worth of nuclear medicine equipment. It has technical co-operation projects and research contracts dealing directly with nuclear medicine instrumentation, especially quality control and maintenance. It engages in training related to maintenance. And finally, its laboratory can test ideas and devices.

One inevitable consequence of the electronics revolution on nuclear medicine instrumentation in developing countries is that the instruments tend to be out of date by comparison with those in advanced laboratories. For one reason, they cannot be written off so frequently on purely financial grounds. More important, the new classes of instrument that come on the market are likely to be expensive, and cannot be afforded. The fact that scanners tend to cost one fifth as much as gamma cameras has meant that laboratories in developing countries have continued to acquire them after they have become virtually extinct in developed countries.

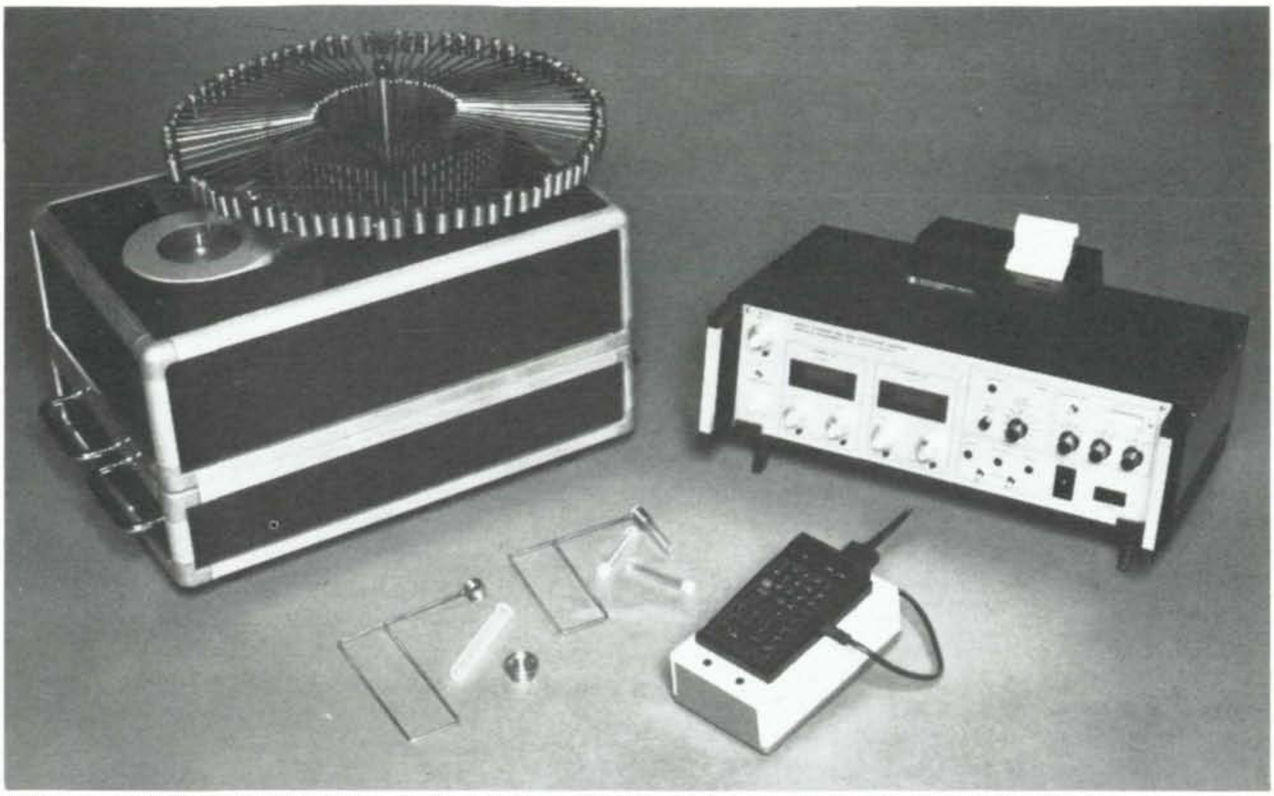
One consequence of this lag in equipment is a mismatch during training. Any fellow trained in imaging today in advanced countries is unlikely to see a scanner, although many of them return to laboratories where that is the only imaging instrument available. Another consequence is that the equipment present in a laboratory is likely to cover a range of technologies from microprocessors back to early integrated circuits, a considerable complication regarding spare parts and skills required for maintenance.

Preventative maintenance

Maintenance remains an important problem despite the improved reliability of modern instruments. From the Agency's survey, reports indicated that 10 to 20% of the instruments are inoperational at any one time, and probably the actual situation is worse. It is useful to consider preventive maintenance and repair separately.

The environment within which instruments are used in developing countries is less favourable than those for which the instruments were designed. The performance of integrated circuits is more adversely affected by high temperature than is that of vacuum tubes, and rapid changes of temperature (e.g. a rise following failure of an air conditioner) could endanger the detector of a gamma camera. Elevated humidity, either naturally occurring or a consequence of air cooling without concurrent dehumidification, may be more serious. Sand, insects, and rodents may also play a role. Probably more important than any of these issues is the electrical power environment. Integrated circuits are much more easily damaged by power surges than were vacuum tube instruments, and such surges are much more common in the power systems of developing countries than of developed.

The Agency currently has in effect an interregional technical co-operation project and a series of research contracts to upgrade maintenance. In each of about 20 countries a national co-ordinator has been identified to oversee the programme, and 2 or 3 pilot laboratories have been selected to test the possibilities of improvement. Special stress is placed on the environment, inasmuch as it is believed that this is one serious hazard that could be largely eliminated. Laboratories are encouraged to monitor temperature, humidity, and voltage levels, and are provided with appropriate



The commercial version of the automatic counter for measuring radioactivity of gamma-emitting samples, designed at the IAEA's Seibersdorf Laboratory using simple and inexpensive components.

measuring equipment if necessary. The importance of humidity control is stressed. More particularly, power conditioning equipment has been provided, along with encouragement in its use. This includes voltage stabilizers, surge suppressors, and "dropout relays". The latter are devices that cut an instrument off from mains power at the moment power fails so that it is not exposed to the surges that commonly accompany restoration of power. Conscientious attention to such protection could prevent many instrument breakdowns.

In developed countries repair is commonly accomplished at this phase of the electronics revolution by the manufacturer's service agent, who alone may have the skill, test equipment, and spare parts. Often this service is covered by a maintenance contract, an insurance policy costing per year about 5 to 10% of the price of the instrument. In developing countries the cost is usually higher because of higher travel expenses for the greater distance. For this reason, as well as the need to "save" money, and difficulties with multi-year commitment of funds, maintenance contracts are seldom in force. Hence a company service agent is often unavailable when needed.

Repair using local resources is often difficult. Most functional parts of modern instruments cannot be repaired if defective; instead the defective component or circuit board must be replaced. Nevertheless, some maintenance skill is required to identify the malfunctioning component, and there are always some elements, mechanical or electronic, where repair can be effected by those who have skill and the confidence that comes from experience.

The acquisition of spare parts is one of the most frustrating tasks in maintenance. With the great diversity of modern electronics, and the grouping of functions in indivisible integrated circuits or printed circuit boards, it is no longer likely that the needed part can be purchased locally. While the order to the manufacturer can be transmitted at the speed of light, and the part returned at the speed of sound, bureaucratic delays of customs and currency exchange can add months to the transaction – even if the cost is negligible. Stocking parts is inefficient, since most of the stock is never needed. A very few laboratories have established small cash accounts with the manufacturers, or a foreign bank or sister institution, and have worked out customs procedures so that they can quickly obtain parts; their example should serve as an inspiration to others. The Agency is attempting to set up such a supply of parts for the pilot laboratories participating in the maintenance programme. Initially orders would be sent to a strategically placed central supplier, whose operation would be capitalized with Agency funds. Continued participation by each laboratory would be conditional upon its replacement of these funds. The objective would be to test procedures, and to acquaint laboratories with the ready availability of parts in the hope that acquaintance leads to addiction.

The Agency supports the training of electronics engineers and technicians through several channels, including fellowships and training courses. The content of training courses must keep abreast of the electronics revolution, which in little more than a decade has shifted attention from hardware devices to software systems. Another problem is that skilled electronics technicians are in such demand because of the penetration of electronics into every walk of life that many beneficiaries of Agency courses are quickly bought away from their original employers (at least if these were medical institutions). To deal with this bottomless pit, the Agency's programme related to nuclear medicine instruments has begun experimenting with "train-the-trainers" courses. If the professionally capable electronics staff at national centres can be encouraged to multiply their hands through training local colleagues, the result might be a cost-effective supplement to advanced training of specialists abroad.

In the last analysis, the solution to the maintenance problem may be less a matter of technology than of psychology (the will to have an instrument operational) and organization (the mobilization of available remedies). Each of the pilot laboratories is encouraged to prepare a maintenance plan: to identify its own needs, and the resources on call in the laboratory or community; to make advance provision for acquisition of parts; to provide essential training for staff. It may be suggested that the Agency should perform an analogous study in its own operations. When it provides equipment, does it assure itself, for example, that the equipment will be covered by a maintenance contract (purchased by the recipient or the Agency), or at least that a cash deposit will be available to allow the user to acquire parts quickly? At present, not often.

Self-help

In very few developing countries are any of the major instruments constructed in the leading laboratories, much less manufactured commercially. It is difficult and expensive to keep knowledge, parts, and test equipment up-to-date in the face of the rapidly evolving technology, and the incentive to construct obsolete instruments is low. Yet it is tempting to imagine that the present phase of the electronic revolution could offer new opportunities for construction. It has been estimated that 80% of the cost of a scientific instrument is now attributable to software (which requires thought more than anything else), rather than to hardware. Hence the unavailability of hardware, or of foreign exchange to acquire it, should be less of a constraint than heretofore in developing countries.

The Agency's laboratory has undertaken a project in this regard, both to make available a useful instrument and to test the concept of self-help. If it is impractical to design and construct *de novo* a high-performance instrument system, and if acquisition of spare parts from abroad presents insuperable bureaucratic problems, then is it possible to assemble an instrument suited to local conditions from high-technology consumer products available in the bazaar? The single most essential instrument in many nuclear medicine laboratories is an automatic counter for radioactivity measurements on gamma-ray emitting samples — for example, to measure the thousands of samples generated yearly in radioimmunoassay procedures. The Agency's laboratory has designed, built, and distributed to laboratories in developing countries several such counters. The counter itself does not come from the bazaar, but its construction is within the capabilities of many national atomic energy commission laboratories. In its present configuration it consists of a well scintillation detector, 2 single-channel pulse-height analysers, scalers, a ratemeter, and a microprocessor. The automatic sample changer does come from the bazaar — a Kodak carousel slide projector (US $250)*, designed for use and abuse in homes throughout the world. The data processor and system controller likewise comes from the bazaar — a Hewlett-Packard HP-41CV programmable calculator, with accessories (US $1000). When the system is connected together, the microprocessor manages the counter internally, while the calculator supervises sample changing and provides data processing. In the author's biased opinion, the data processing is better than that of any currently available orthodox commercial counting system. If sample changer and calculator break down, the counter can be used manually. If the sample changer alone fails, automatic data processing can still proceed on manually changed samples. Counter and calculator are powered by rechargeable batteries, hence are almost invulnerable to power disturbances including power failures of a few hours' duration. If power fails temporarily during an automatic run, thereby interrupting sample changing, the microprocessor holds the measurement suspended, without error, until sample changing can continue upon return of power. A commercial version of this instrument costs about half as much as normal automatic sample counters.

Revolution will continue

The electronics revolution has brought and will continue to bring rapid changes to the technology of nuclear medicine instrumentation, giving greatly increased capability and reliability. Along with the advantages have come some disadvantages in developing countries, a comparatively small market for which the instruments have not been optimized. A number of measures can be taken to overcome these disadvantages, some organizational, and the Agency is encouraging their introduction.

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* This use of the slide projector was proposed by W.J. Palenscar.