Physical principles of scintinscanning

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Physical Principles of Scintiscanning

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Introduction

The term "scintiscanning" has come to be applied to a technique whereby the distribution of radioactivity in the body of a patient is recorded in the form of a two-dimensional scan. The detecting device is a suitably collimated scintillation counter, mechanically driven and linked with a recording device which gives a visual, and, more important, a permanent record. As is clearly shown in succeeding papers, this particular technique is at present the most widely used for clinical studies. However, the scintiscanners currently available merely exemplify the present level of technical development in a field where considerable progress has been made in the past fifteen years, and there is no evidence for believing that technical improvements will not be introduced at a comparable rate during the next decade. Although the application of established physical principles is important in the development of scanning instruments, many other criteria have to be considered. In the final analysis, radioisotope scanning methods and instrumentation have to be judged according to whether they provide valuable clinical data, at a reasonable cost and without excessive hazard to the patient. On this basis, it is possible to review clinical isotope localisation methods in general, and scintiscanning techniques in particular, from a somewhat pragmatic point of view. A comprehensive and authoritative review of the technical aspects of medical radioisotope scanning is already available in the proceedings of the Seminar sponsored by the International Atomic Energy Agency and the World Health Organisation. A detailed manual on the practical aspects of scintiscanning has also been produced by the Oak Ridge Institute of Nuclear Studies.

The nature of the problem

From the physical point of view, the basic problem can be defined as follows. In a given time, it is necessary to determine the distribution of radioactive material over two dimensions with adequate resolving power and with minimal radiation dose to the patient. It should be noted at the outset that time is the factor over which the operator has least control. Firstly, the time factor may be determined by the kinetics of the distribution processes of the isotope within the patient. Secondly, there is a limit to the time for which a patient can be expected to remain still without discomfort. It has not, perhaps, been sufficiently stressed in the literature that if the patient makes even a slight movement during a scanning procedure the quality of the record obtained may be grossly impaired.

Given that a certain amount of time is available, the problem then becomes one of achieving the maximum degree of resolution with the minimum tracer dose. In general these two requirements conflict with one another; and it is usually possible to evaluate new developments in scintiscanning in terms of their success in achieving the most favourable compromise.

Resolution versus sensitivity

Much of the earlier clinical work on radioisotope scanning was carried out using single aperture systems where the radiation detector was fitted with a cylindrical collimator. The resolving power of such a system, that is to say the ability to detect radioactivity selectively from a restricted region, or to localise a small lesion, is more or less inversely proportional to the diameter of the aperture. However, the observed count rate from an extended source decreases as the fourth power of the diameter of the aperture. Since the observed count rate is subject to statistical fluctuations, which vary as the square root of the number of counts recorded, it follows that a two-fold increase in resolving power achieved by reducing the aperture is obtained at the cost of at least an eight-fold reduction in the accuracy of the radioactivity determination. Moreover, the statistical errors increase considerably as the observed count rate becomes comparable with the instrumental and environmental background count. Thus, with the simple cylindrical collimator detector system, there is a limiting degree of resolution of the order of 2 or 3 cm where any improvement by reducing the aperture necessitates a prohibitive increase in either the tracer dose or the duration of the measurement. This relationship between resolution and sensitivity can be compared with the situation encountered in photographic work where the exposure time for a given light intensity varies inversely as the square of the aperture. It is evident that until scanners are developed where the relationship between exposure time and aperture is similar to that of the optical camera there will always remain scope for improvement.

As long as we have the situation where a high degree of resolution has to be obtained at the cost of a considerable reduction in sensitivity, it is evident that in any given clinical application it is best to employ resolving power which is no better than required to give the necessary information. For example, one well established localisation test is the use of radioactive isotopes for localisation of the placental site. This can be done perfectly satisfactorily without any collimation at all, reliance being placed entirely on the inverse square law. Other tests such as the assessment of patients with varying degrees of splenomegaly can be carried out with a relatively poor degree of resolution. The requirement for maximum resolution arises when one is concerned with the detection of small lesions, cysts and tumours. It follows, therefore, that if an instrument is required for a variety of clinical tests it is desirable that it should be possible to vary the resolving power according to requirements in the same way as the photographer can vary his lens aperture. In fact, this can be done to only a limited extent, if at all, with most of the currently commercially available equipment.

Major developments in scintiscanning

In the light of the above considerations it is possible to assess the importance of a number of technical improvements which have been made in recent years.

The first and most important advance was made possible when scintillation counters with sodium iodide crystals became available since they are some 30 to 50 times more sensitive to gamma-radiation than Geiger-Muller tubes used in the earlier work.

Further major improvements have been achieved by the use of multichannel focused collimators. In effect one achieves the resolving power of a small diameter collimator, but by having many apertures diverging to a large crystal it is possible to substantially offset the reduction in count rate. Were it not for the fact that the lead septa which define the multiple apertures obstruct part of the crystal, this arrangement would tend towards the ideal system where the sensitivity varies as the square root of the resolving power.

A further valuable development has been the introduction of gamma-ray spectroscopy or pulse height analysis, the main effect of which is to reduce the environmental and instrumental background count, thus lowering the limit of sensitivity of the detector. The larger the sodium iodide crystal, the more effective this technique becomes since the gamma ray energy is absorbed more effectively; and this is a further advantage of the multi-channel collimator systems referred to above.

Another important technique which is applicable only to isotopes which emit positrons depends on the use of two scintillation detectors in line on opposite sides of the region being scanned. These are connected through a coincidence circuit to pick up the two 0.5 Mev gamma-ray quanta which result from the annihilation of a positron. Since these radiations are emitted in opposite directions it is not necessary to depend on lead shielding for the collimation. Thus the effective aperture of this system is defined by the crystals themselves and not by the diameter of holes some distance in front of it. Hence for a given resolving power the detector can be mounted closer to the source with a corresponding increase in sensitivity.

The application of the above mentioned physical principles has accounted for most of the progress made in scintiscanning in recent years and the general design of most of the currently used detectors is based on these principles.

The gamma-ray camera

The basic weakness of the commonly used scanning systems is that at any given instant the detector is only recording radioactivity from a very small portion of the field being studied, information in the form of counts from the remainder of the field is rejected by the collimation system and is therefore wasted. If this wastage of information could be eliminated by using a scanning system which continously recorded the activity of the whole area a substantial increase of sensitivity would be obtained. Various methods have been tried based on the use of multiple crystals and photographic films but the most promising recent development is the "gamma-ray camera" originated by Anger which operates on the principle of a pin-hole camera. The radiations enter the single aperture and produce scintillations in a crystal of relatively large diameter. This crystal is viewed by seven or more photomultiplier tubes, which are connected through suitable circuits so that a spot of light appears at the appropriate part of an oscilloscope screen or image storage tube. The resulting pattern of dots can be displayed and photographed to give a picture showing the distribution of radioactivity in the region viewed. This particular system, in addition to its potential increased sensitivity, has the great virtue that there are no mechanical devices or moving parts; and in clinical practice it can be set up and directed in much the same way as a diagnostic X-ray tube.

Gamma-ray energy

When isotopes other than positron emitters are being used, it is preferable to use those which emit a single low energy gamma-ray. It is then possible to achieve adequate collimation with much lighter collimators, this in turn reduces mechanical difficulties. Furthermore, absorption of gamma-ray energy within the crystal is much more efficient, with the result that background reduction by pulse height analysis is correspondingly more effective. For example, there is now increasing interest in the use of I^{125} for thyroid scans in preference to I^{131}.

Presentation of data

Even with pulse height analysis, effective lead shielding and a low background environment, there will always remain a certain number of marks on the scan due to background radiation. Much of this is due to radioactive material present in the vascular system and in tissues other than the one of interest. Improvement in this respect is likely to come with the development of improved tracer compounds with more favourable metabolic properties so that their localisation in the tissue of interest becomes more specific, rather than by physical techniques.

A further problem arises when there is a requirement for a high degree of contrast in the scan so that regions can be detected where the concentration of radioactive material differs only slightly from that in the surrounding tissues. Numerous techniques have been developed whereby the response of the instrument is made non-linear with a view to improving contrast and reducing the background contribution. These include background suppression circuits, photoscanning methods and the use of variable scaling factors. In effect, these techniques reject a certain amount of the information recorded by the equipment as being unwanted data. This approach to the problem has been strongly criticised by *Brucer* in the Oak Ridge Manual on the grounds that the interpretation of the scan by a clinician is, in any case, a subjective process; and the introduction of a further subjective element, that is, a technician who decides on the instrumental settings which appear to give the best picture, is a serious disadvantage. The point stressed here is that a scan which may look well from the artistic point of view is not necessarily informative and can in some cases be misleading. This criticism appears to be adequately met in the newer instruments where all the data is recorded on wire or tape or on an image storage tube and subsequently played back under varying conditions so that the individual who has to interpret the scan in clinical terms can also select the presentation which he prefers.

Another approach to the problem of the contrast and ease of interpretation of the scans is the use of a printer which records regions of differing activity by making marks in different colours. Thus, at present, the type of record preferred is ultimately a matter for personal preference and does not depend a great deal on physical principles.

Although the main advantage of the scintiscanner is generally regarded as being its ability to give a permanent objective record, it is evident that there are still certain subjective elements involved both in the obtaining of the record and in its interpretation, particularly when small differences in radioactivity are being studied. In this connection, it may be worth noting that the human ear is a very sensitive device for detecting small changes in count rate; and if one is not primarily interested in the permanent record, it is often possible to carry out clinical scanning procedures quite adequately by using much less expensive equipment which gives an audible signal.

Summary

The dominant factor affecting scanning measurements is the available time. This may depend on the kinetics of physiological processes or it may be determined entirely by practical considerations. During the available period, it is necessary to measure radioactivity as a function of position over a two dimensional scan. Maximum resolving power is required in order to detect small lesions, and maximum sensitivity is necessary to ensure minimal radiation dosage to the patient. These two requirements are in direct conflict with one another. Since the degree of linear resolution required is dictated by the nature of the clinical problem, it is evident that the basic physical problem is the achievement of maximum sensitivity for a given resolving power. In the limit, the level of background radiation determines the sensitivity of the apparatus; reduction of the background level is therefore an important contribution to the sensitivity. Finally, there are various methods for presentation of the available data so that they may be more readily interpreted by the clinician, but the choice between these is determined more by subjective factors than by basic physical principles.

Zusammenfassung

Der dominierende Faktor, welcher szintigraphische Messungen bestimmt, ist die verfügbare Zeit. Diese mag von der Kinetik der physiologischen Vorgänge abhängen oder durch praktische Gesichtspunkte vollständig bestimmt werden. Während des verfügbaren Zeitabschnitts ist es notwendig, die Radioaktivität als Funktion eines in zwei Dimensionen bewegbaren Detektors zu messen. Um kleine Läsionen entdecken zu können, ist ein maximales Auflösungsvermögen notwendig und eine maximale Empfindlichkeit, um dem Patienten eine minimale Strahlendosis zu sichern. Diese beiden Anforderungen stehen in direktem Gegensatz zueinander. Da der Grad der verlangten linearen Auflösung durch die Natur des klinischen Problems bestimmt wird, ist es klar, daß das grundlegende physikalische Problem die Ermittlung der maximalen Empfindlichkeit für ein gegebenes Auflösungsvermögen ist. Innerhalb gewisser Grenzen bestimmt das Niveau der «Background»-Strahlung die Empfindlichkeit des Apparates; die Herabsetzung des «Background» ist deshalb ein wichtiger Beitrag zur Empfindlichkeit. Endlich gibt es verschiedene Methoden für die Darstellung der verfügbaren Daten, so daß sie vom Kliniker leichter interpretiert werden können; aber die Wahl dieser Methoden wird eher durch subjektive Faktoren als durch grundlegende physikalische Prinzipien bestimmt.

Résumé

Le facteur principal qui influence les mesures de scintigraphie est le temps disponible. Il peut lui-même dépendre de la rapidité des processus physiologiques ou d'autres considérations d'ordre pratique. Durant la période de mesure, il est indispensable de déterminer la radioactivité en tant que fonction dans un plan à deux dimensions. Pour déceler de petites lésions, il est nécessaire de balayer l'organisme avec un faisceau à puissance maximum, et d'autre part, il faut une sensibilité maximale pour assurer au malade un minimum de radiations. Ces deux exigences sont à l'opposé l'une de l'autre. Comme le degré de résorption linéaire est donné par la nature du problème clinique, il est évident, qu'au point de vue physique, le problème de base consiste à assurer une sensibilité maximale pour une source donnée en mouvement. Dans les cas limites, c'est le degré de radiation du milieu ambiant qui détermine la sensibilité tolérable de l'appareil; c'est pourquoi la diminution de la radiation du milieu ambiant joue un grand rôle dans la détermination de la sensibilité. Enfin, il y aurait différentes manières de présenter les données physiques pour

les rendre plus faciles à interpréter pour le clinicien, mais le choix entre ces différentes manières est plutôt dicté par des données subjectives que par des principes physiques.

Riassunto

Il fattore dominante che influenza le misurazioni scintigrafiche è il tempo disponibile. Questo può dipendere dalla dinamica di processi fisiologici o essere interamente determinato da considerazioni pratiche. Durante il periodo disponibile è necessario misurare la radioattività quale funzione di posizione su un detettore a due dimensioni. Sono necessari un potere massimo di risoluzione, al fine di mettere in evidenza lesioni minime, e una sensibilità massima, per applicare al paziente dosi minime di radiazione. Questi due requisiti sono in diretto contrasto fra di loro. Dal momento che il grado di risoluzione lineare richiesto è imposto dalla natura del problema clinico, è evidente che il problema fisico di base sta nel raggiungimento di una sensibilità massima per un potere di risoluzione dato. Nei casi limite, il livello della radiazione di base determina la sensibilità dell'apparecchio; la riduzione del livello di base è perciò un importante contributo alla sensibilità. Infine vi sono vari metodi per la presentazione dei dati disponibili, così che essi possono essere interpretati dal clinico in maniera più leggibile, ma la scelta fra questi è determinata più da fattori soggettivi che da principi fisici basilari.

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