Radionuclide Emission Computed Tomography – 3D Imaging

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Introduction:

Conventional radionuclide imaging in nuclear medicine is usually performed with planar gamma camera that provides only a two-dimensional (2-D) representation of radiopharmaceutical distribution within the organ. Of late, new approaches and notable advances in medical imaging have resulted from new concepts and developments in computer science and applied mathematics. Although the mathematical sciences were used in a general way for image processing , they were of little importance in biomedical work until the development in the 1970s of computed tomography (CT) for the other modalities, which are being developed and now well established , are ultrasound and electroencephalography, as well as new techniques of holography, impedance tomography and magnetic source imaging. It is worth pointing out that while the reconstruction techniques for 3D final images of many of these techniques bear many similarities to each other, the technologies involved in each are entirely different. In nuclear medicine the recent trend is towards digital multidetector, faster processors, attenuation corrections as well as high energy (511 Kev photons) emission imaging.

Emission Computed Tomography (ECT):

ECT provides 3D distribution of radiotracer in an organ leading to Single Photon Emission Computed Tomography (SPECT) and Positron Emission Tomography (PET) scans.

(a) Single and Multidetector SPECT system:

Off late, the biggest actual advance in SPECT systems in nuclear medicine has been the use of multiple detectors and variable angle

geometry instead of conventional single head. For example, SPECT images of the brain can be performed using either multidetector or rotating (SPECT) gamma camera systems. Each imaging system has its own advantages; the choice of equipment depends on the level of utilization and on the purposes for which the technique will be applied.

(b) Positron Emission Tomography (PET):

The basic principle of the PET is that two 511 Kev photon are emitted in opposite directions (180^{o}) following the annihilation of a positron and an electron. Thus by positioning two detectors around a patient one could determine the line along which disintegration occurred. The availability of physiologically interesting positron-emitting radiopharmaceutical from the cyclotron and suitable instrumentation, as well as the development of algorithms for image reconstruction, provides the impetus for PET.

Detectors and crystals: The fundamental physical difference between PET & SPECT is the use of annihilation coincidence detection (ACD) or in the detection of two 511 Kev photons. ACD detects only those pair of events that are detected within a narrow time interval (typically 5-20 ns). Events registered in only one detector are rejected electronically and hence the name electronic collimation. Although Nal (Tl) is satisfactory for most imaging systems used with ordinary gamma ray emitters, the 511 keV annihilation photons require detectors with greater stopping power for efficient detection. Most crystals are 3 to 6 mm thick and they are not hydrophilic. Bismuth germanate ($Bi_4Ge_3O_{12}$) is currently the preferred detector material (50% more efficient than Nal (Il) crystals), even though its scintillation light yield is somewhat low (15%) and decay time some what long (which limits count rates and poorer energy resolution (20% FWHM at 511 keV) than sodium-iodide crystals. The coincidence time window is normally set for 10 to 20 ns. The inferior time resolution causes larger accidental detentions and greater dead times.

All commercial system have approximately the same characteristics and they have rings of bismuth germanate detectors individually coupled or coded to photomultiplier tubes. Employment of cross coincidence between rings results in more image levels than the number of individual rings of crystals; thus a four ring system can give data for seven planes. The recent trends in positron instrumentation have been in two directions. The first is toward high resolution positron instruments; the second is toward the use of time-of-flight means estimation of position of the origin of the photons b y estimating the

difference between their arrival times at the two detectors. At time difference in arrival at two detectors of 300Pico seconds corresponds to a 9-cm travel difference at the speed of light ($3x10^{10}$ cm) or a postion resolution of 4.5c. FWHM. Imaging devices in which this concept is used cerium fluoride (CeF_3) or barium fluoride (BaF_2) crystals. These crystals have very short resolving times and coincidence localization can be obtained to within a fraction of a nanosecond, permitting improved sensitivity and signal to noise ratio. Unfortunately, these crystals typically have poor energy resolution and less light output than BGO crystals. The main advantage of TOF-PET is to improve statistical data, not spatial resolution. It is hoped that time of flight instrumentation will improve further the quality of image and this concept is being implemented in newer instruments. High-energy resolution is achieved by using many thin detectors in a ring configuration. Since PM tubes have relatively large dimensions, various coding scheme have been proposed to identify individual detectors, and this aspect of the design may become a limiting factor unless a new phototube is developed.

Diagnostic utilities of PET:

PET is a diagnostic method that creates high-resolution 2D & 3D tomographic images of the distribution of positron emitting radionuclides in the body. The radio-labelled compounds include substrates, ligands, drugs (involved in normal or pathological biochemical pathways for instance, sugars, fatty acids and amino acids), antibodies, neurotransmitters and many other molecules that are tracers for specific biological processes (functional images).

PET tracers are administered intravenously, distributed according to the blood flow and utilized or processed in a manner virtually identical to non-radioactive counterparts. The images produced are functional indexes of blood flow, glucose metabolism, amino-acid transports, protein metabolism, neuro-receptor status, oxygen consumption or even cell division. Since only tracer amounts of the substances are administered, no pharmacological effects occur and there is no perturbation of the targeted biochemical process.

PET can provide functional image of regional biochemistry than is more sensitive and accurate for detecting the presence of a tumour. For example using ^{18}F fluorodeoxyglucose, a tracer of glucose metabolism. The localized increase of glucose metabolism in a tumour can be detected much earlier that in CT scan and will provide unique information on the degree of malignancy as a result of increased

utilization of glucose. Some important applications of PET are listed below:

(a) Study of epilepsy (nervous system disorders that cause convulsive seizures).
(b) Evaluation of stroke (blood clot or bleeding in the brain).
(c) Study of dementia (for example in patients with Alzheimer's or Parkinson's disease) imaging and evaluation of brain tumours.
(d) Evaluation of coronary artery disease and detection of transient ischemia (poor blood flow).
(e) Differentiating malignant from benign growths as well as showing the spread of malignant tumors. The various applications in oncology are: differential diagnosis, preoperative staging of cancer, and detection of residual tumour after surgery, demonstration of recurrences and follow-up of therapy prognostication of the progress of disease.

Advantages and Disadvantages of PET:

An advantage of PET over SPECT is its much greater efficiency (nearly 10-20 times that of SPECT). Physical collimation in SPECT, results in loss of many available photons. For positron emitter radionuclides it is necessary to have hospital based cyclotron or for some positron emitters a portable generator. In contrast, single photon emitters for instances ^{99m}Tc and ^{123}I , are easier to work with because of their longer half-life. PET techniques has the potential for measurement of glucose, fatty acid, amino acid and other substrate metabolism as well as receptor concentration in the body. It is a valuable new research tool for the investigation of diseases such as aging, schizophrenia, artherosclerosis and oncology as mentioned above. Future PET lies further on advancement and improvement of instrumentation, radiopharmaceuticals and kinetic modeling.

There are many factors which limit the ultimate resolution of PET. The most important are the distance the positron travels through tissue annihilation, the angular deviation of $\pm$0.25 from 180 for the two photons emitted on annihilation, finite detector dimensions and statistical aspects of reconstruction. Resolution and quantitative performance are also affected by the distance between detectors (detector ring diameter). The closer the detectors are to each other and to the source, the greater the resolution. Unfortunately, the smaller the diameter of the scanner ring, the more likely scattered and random coincidences will be recorded.

Some of the shortcomings are overcome in PET by applying attenuation and scatter correction. Attenuation correction is easily accomplished (by obtaining a transmission scan utilizing ^{68}Ga or ^{137}Cs). Also , positron –emitting isotopes of carbon, nitrogen, oxygen and fluorine occur naturally in many compounds of biological interest and can therefore be readily incorporated into a wide variety of useful radiopharmaceuticals . Since collimation is done electronically so no collimator is required, leading to relatively high sensitivity. The major problem with PET is cost. The short half life of most positron emitting isotopes requires an on-site cyclotron, and the PET scanner itself is significantly more expensive that single-photon cameras. Nevertheless, PET is widely used in research studies and is finding growing clinical acceptance, primarily for the diagnosis and staging of cancer as discussed above.

Positron Imaging with SPECT:

A major thrust in research and development is currently positron imaging of PET radiopharmaceuticals with gamma cameras, specifically ^{18}FDG. Positron emitting radionuclides could be used in two ways : (a) collimated detection of one or both of the two photons in non-coincidence detection of both photons by opposite detectors of a dual head SPECT.

(a) Using 511-KeV collimator

In theory, positron emitting radionuclides could be used in SPECT in two ways. Either collimated detection of one or both of the two photons in **non-coincidence** mode (i.e by one or more collimated heads in a conventional SPECT system) or collimator-less **coincidence detection** of both photons by opposing detectors (i.e , by a dual head un-collimated 180^{o} SPECT system) . Most manufactures have now developed 511-keV collimators and the thickness of the crystal is increased the further (from 3/8” to 5/8”) in order to increase the stopping power of 511 KeV. In practice, most 511 KeV collimators have significantly lower geometric sensitivity than lower energy (e.g. 140 KeV) collimators. In spite of the difficulties in designing 511-KeV collimators that are capable of producing images with adequate signal-to-noise ratio, several important preliminary studies suggest that such an approach can provide useful clinical data.

(b) Collimator-less coincidence imaging:

To improve sensitivity and resolution several companies are now demonstrating dual head cameras operating PET-like coincidence mode without collimators. The photons may be detected either in singles mode using a 511-keV collimators with "conventional" SPECT system or dual-head SPECT system without collimators in a coincidence mode. The opposite cameras are electronically configured in coincidence and the coincident detection of two 511-keV annihilation photons is used to define a coincidence line that passes through the annihilation site. This annihilation site differs from the positron emission site by about 1 mm, which fundamentally limits the achievable resolution in coincidence imaging. However the lack of collimation, coupled with high speed electronics permits spatial resolution only slightly worse than the intrinsic resolution of the camera (i.e. about 4-5 mm) whereas the sensitivity is quite high than with collimated SPECT .

In general, these devices offer better imaging characteristics than SPECT but are inferior to conventional PET. The cost of upgrade to coincidence instrumentation is estimated at US$ 1,00,000-2,00,000 by most vendors. The count rate of cameras operating without collimators remain a technical problem, since only a small fraction of count detected in coincidence is used to form the image.

In short, coincidence imaging of a positron emitter with dual head SPECT is an alternative to the costly PET equipment. Coincidence imaging is still at infancy stage and clinical evaluation showed very encouraging results. The performing pf PET studies on a conventional gamma camera has created a lot of excitement in the nuclear medicine community. Latest trends to Dual Isotope Simultaneous Acquisition (DISA) of low energy perfusion tracer MIBI and FDG will help in detection of hibernating myocardium that cannot otherwise be seen.