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BASIC TECHNOLOGICAL ASPECTS AND OPTIMIZATION PROBLEMS IN X-RAY COMPUTED TOMOGRAPHY (C.T.)

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1 INTRODUCTION

The principles of Computed Tomography (C.T.) have been widely reviewed in published works and they are not reproduced in this paper.

Very important efforts have been invested for the last decade in this field, so that several generations of C.T. machines have been successively proposed to the radiologist community.

The main sources of image artefacts have been investigated, and now, it can be assumed that most of the machines are capable of producing good image quality in clinical routine examination. But it does not mean that new technical advances could not take place in the near future. Physical limitations have not yet been reached for several characteristics and new improvements can be expected in different fields : more powerful X-ray tubes, new types of high resolution mono and multi-slice detectors, integrated technology for high density data acquisition system, fast reconstruction processing systems, etc... Nevertheless, competition will take place in the near future between C.T. imaging and N.M.R. imaging and it is clear that new efforts in C.T. technology will be accepted by the manufacturers only if X-ray C.T. always represents a significant part of diagnostic imaging.

The current status and future prospects of physical performances are analysed and the optimization problems are approached.

2. C.T. ARCHITECTURE EVOLUTION

The original system developed by Hounsfield (1973) for brain employs a translate-rotate movement in which the X-ray tube and a single detector scans the patient along a large number of sets of parallel rays. Very good image quality is obtainable with this basic method as long as the object to be imaged is stationary. The scattered radiation rejection rate is excellent, the source-detector combination can be moved in small steps involving a very good linear sampling, and the level of artefacts is lower than with one-motion machines.

The second scanning mode has been introduced to speed up the data collection process without losing the advantages of the first one. It uses an array of detectors and a translate-rotate motion for the source-detector system. For each linear scan, data is collected for many sets of parallel rays (typically 20 to 60). Such scanners have been built with a typical exposure time of several tens of seconds. The image quality is excellent and that type of C.T. remains a great interest for brain imaging. The "fan beam" method involves only one motion and it represents a widespread solution (Third generation machines). The array of detectors is large enough to enclose the whole reconstruction area and the X-ray source multidetector combination rotates around the object. For each slice, the data collection process can be achieved in a few seconds. That type of C.T. is well suited for whole-body imaging since organ motion artefacts are considerably reduced. This arrangement requires a very high stability for the detector and data acquisition electronics. Each detector cell images a circular path around the center of rotation and a very small difference of response between adjacent cells can generate circular artefacts. Large efforts have been invested by most manufacturers and that difficulty is now overcome. This architecture is the most widespread one because it can be used now as well for brain as for whole body imaging, and it represents a trade off between the performance and the technological complexity.

An alternative solution consists in employing a stationary circular array of detectors and a rotating X-ray source. It is a good approach for reducing motion artefacts. An exposure time of one second can be reached. But this scanning mode requires a larger number of detectors than the fan beam method and it needs very thin detectors since each cell has to detect on a large range of angular directions. Also, the scattered radiation contribution is higher than for the previous method.(1)

One second exposure time is approximatively an upper limit for C.T. with mechanical motion. C.T. imaging for fast moving organs, such as the heart, requires new technological and data collection solutions. Several approaches have been investigated, but it is not the purpose of this paper to describe this topic.

3 MAIN CHARACTERISTICS OF C.T. MACHINES

3.1. Physical characteristics

The density resolution and the spatial resolution are the two major physical characteristics.

3.1.1. The density resolution

The basic limitation to the density accuracy is due to the statistical nature of X-rays photons. Therefore a comparison between two machines has to be made with the same radiation dose. The physical limitation is reached when all the incident photons emerging from the object are detected and when the scattered radiation rejection by the detector is total. So, the density resolution test is an indirect measurement of the detection efficiency (including collimation, edge effects,...) and of the capability of the detector to reject the scattered radiation from the object and from the detector itself.

With the normal condition for testing, the density resolution is currently 0.2 to 0.3 % for a modern C.T. machine.

3.1.2. The spatial resolution

The spatial response is typically of 12 to 15 pairs of lines per centimeter (pℓ/cm) for high performance machines and 7 to 8 pℓ/cm for conventional machines.

This value does not represent a physical limit. It is a trade-off between technological, electronic, and data processing complexity. The slice thickness is currently of 8 to 10 mm in order to image a complete organ with a reasonable number of slices. So, each voxel is a long parallelepiped and that shape generates image artefacts as it will be discussed later. Furthermore, the detector technology becomes more difficult when the number of cells is increasing. Also, data collection and data processing requires faster electronics.

3.2. Operating characteristics

Exposure time per slice represents a major characteristic in order to minimize the image artefacts due to the organ motion.

The data collection does not exceed a few seconds in most machines.

Furthermore, it is essential to be able to collect 10 to 20 successive slices to image an entire organ. It means that the image reconstruction time must be reduced to a few seconds and that the heat load of the X-ray tube is large enough to accept such a cadence. X-ray tubes with large rotating anode using the thermal properties of the bulk material have been specially designed for C.T.

3.3. Radiation dose utilization

It is essential to minimize the dose to the patient for a given quality of image. It means that the number of incident photons which do not participate to the data collection must be as low as possible.

The X-ray beam has to be carefully filtered to minimize the low energy photons contribution from the X-ray spectrum. These photons increase the patients' dose but they do not yield a useful signal because they are absorbed inside the patient.

The shape and the size of the focal spot of the X-ray tube are also very important factors. A large focal spot is required to maximize the radiation output, but the radiation dose utilization coefficient is reduced because of the fan beam collimation. This effect is particularly important for thin slice imaging. Also, the spatial resolution in the transverse plane decreases.

The stopping power of the multidetector is of course an essential factor for radiation dose utilization. Each cell of the detector has to be collimated in order to minimize the scattered radiation contribution from the organ. So the number of useful photons is reduced by this collimator, and the overall efficiency, which is the product of the quantum efficiency and the geometric photon efficiency, does not exceed 60 % in practice.

The radiation dose is maximum at the level of the skin. It is currently of 2-3 rads for a conventional machine.

Many possible improvements in X-ray C.T. are restricted by the radiation dose. For instance, to decrease the pixel width (spatial resolution) by a factor of 2 with the same signal to noise ratio (in terms of statistical noise), the dose has to be increased by a factor of 8. Also, to improve the density resolution by a factor of 2, the dose has to be increased by a factor of 4.(2)

3.4. Parameters to be considered for C.T. imaging

Independently of the above mentioned physical and operating characteristics, different parameters have to be taken into account for evaluating C.T. image quality. (3)

3.4.1. "Beam hardening" effects

Because the photons attenuation is lower when the energy is increasing, the energy distribution spectrum of the X-ray beam changes as it passes through the object. It is the phenomenon of "beam hardening". A calibration procedure using several attenuation phantoms is needed in order to determine the detector response to a polychromatic X-ray beam for different attenuation thicknesses.

3.4.2. Scattered radiation contribution

For large objects (Ø ∿ 40 cm), the scattered radiation contribution can reach the same order of magnitude as the useful signal itself. It is a low spatial frequency spurious signal which degrades the signal to noise ratio and the image contrast. It is essential to reject it in putting a fan beam collimator just in front of the multidetector. Its geometrical accuracy, its positionning and its stability in rotating motion require very stringent demands. To illustrate that statement, it is useful to recall that each measurement has to be made with an accuracy of 2-3‰ in the whole dynamic range which can reach about 500 for large objects. So, a very small geometrical distortion can generate strong circular artefacts since each cell images a circular path around the center of rotation.

3.4.3. "Partial volume" effects

10 mm thick slices are currently used to scan a complete organ which requires 10 to 20 successive slices. These values correspond to a reasonable exposure time for the patient (problems of motion artefacts) and they are compatible with the heat load of the present X-ray tubes. The size of each voxel is about 1 x 1 x 10 mm^3. As the anatomical structures present complicated shapes with strong gradients (bones and soft tissue) it means that the measured attenuation is not the true one. This phenomenon is called "partial volume" effect ; it can be emphasized by the focal spot size of the X-ray tube. One way of combating this is to choose smaller slice thickness ; that is currently employed to image complex structures with strong attenuation gradients, particularly in brain imaging.

3.4.4. Technological parameters

- Mechanical stability is of major importance. C.T. imaging requires very accurate measurements ($\sim$ 2-3 %) on a large dynamic range ($\sim$ 500). This data has to be collected from a heavy X-ray source-detector combination rotating around the patient. It supposes that very stringent demands have been solved.

- X-ray tube : the thermal performance requires a large rotating anode with a heavy bulk material, and the measurement accuracy needs a very stable focal spot. These two conditions are very difficult to obtain and special tubes have been designed for C.T. Particularly rotating anode wobble and filament vibrations generate severe artefacts on the reconstructed image. Also, the HV supply must be very stable ($\sim 10^{-4}$ %).

- Detector : the detector is the main factor of C.T. design and performance. It operates in current mode because the photons flux is too high to work with pulse method. (The direct flux is about 10^{10} events/second/cell). Its design must take into account several major factors :
  . a high stopping power
  . a good linearity on a large dynamic range ($\sim$500)
  . a good packing fraction
  . a negligeable crosstalk between adjacent cells
  . a high stability of response
  . a fast time of response
  Two types of detectors have been designed for C.T.

- Linear array of solid state detectors : each cell is made of a scintillator optically coupled to a low leakage current photodiode working in photovoltaic mode. This arrangement exhibits a good packing fraction and a high stopping power. It is essential to choose a scintillator which does not yield a long period light emission component in order to avoid pile-up effects between successive measurements. Bismuth-germanate (BGO) and caesium-iodide (CsI) have been employed, but now Cadmium tungstate (Cd W O_4) is preferred because it combines three major advantages : the light emission is well suited to the photodiode sensitivity, it is not hygroscopic, and it has no long period light component. This solution is well adapted to the fourth generation machines (a complete ring of stationary detectors) because thin and efficient detectors can detect on a large range of angular directions. Also, it has been employed for third generation machines (fan beam method).

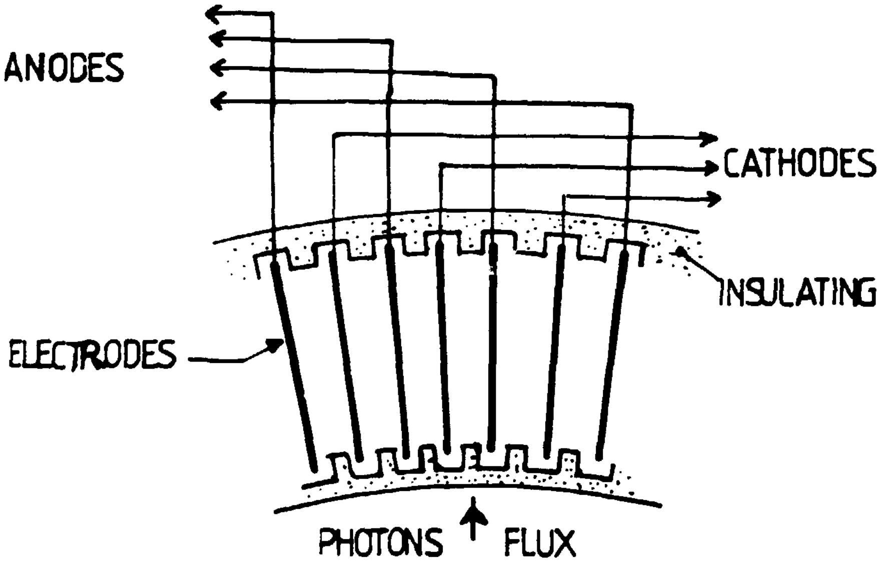

Figure 1 : Principle of an ionization multidetector

- Ionization multichamber : the figure 1 shows a typical arrangement of such a detector. The electrodes are focused on the X-ray focal spot and they have a triple function :
  - . collimation for the scattered radiation from the object
  - . collimation for the scattered radiation and fluorescent X-rays produced inside the detector itself
  - . collection of the charges created by ionization in the gas

Xenon is the best choice for this application because of its high stopping power. No purification system is required since the chamber operates in ion collection mode. The time response is compatible with the time sequence of the data. For instance, for a 1 mm interelectrodes space, a 30 atmospheres pressure and a 1 KV HV supply, the collection time is about 1,5 ms.

This solution exhibits major physical advantages :

- a good linearity of response on a large dynamic range
- a very good stability
- no pile-up effects
- a good quantum efficiency

Nevertheless, extreme mechanical and electrical care is required for the insulating, the positioning and the mechanical holding of the electrodes. Small deviations from the ideal mechanical and electrical conditions generate severe artefacts.

Now, most of these technological difficulties have been overcome, and this solution has been chosen for a large number of fan beam machines.

Whatever the detector may be, the usual value is about 0.5 mm aperture, and currently, one thousand cells linear array have been manufactured.

3.4.5. Other parameters

Several other parameters have to be considered for a C.T. design, such as :

- **The** measurements calibration method
- The X-ray beam monitoring
- The linear and rotating sampling problems
- The X-ray energy optimization as an function of the organ to be imaged

Their discussion is beyond the scope of this paper.

4 CURRENT STATUS AND FUTURE PROSPECTS OF C.T. PHYSICAL PERFORMANCES

The current physical and operating characteristics of the commercially available high level C.T. are :

- spatial resolution : 12 to 15 pairs of lines per centimeter
- minimum exposure time : 1 to 2 seconds
- slice thickness : adjusting from 1 to 10 mm
- number of sequential slices : 15 to 30

4.1. Density resolution

The density resolution is difficult to characterize since it depends on many factors : the radiation dose, the X-ray energy, the slice thickness, ... A typical value of 2 to 3°/$_{oo}$ is currently obtained on brain imaging.

This characteristic exhibits a physical limit which is given by the number of photons needed to obtain a given density resolution due to the statistical nature of X-ray photons. The present performance is close to this physical limit. For the photons emerging from the object, the overall detection efficiency presently reaches 60 %. For the incident photons entering into the object, some advance can be expected in using smaller focal spot tubes, but that approach is very difficult to obtain because of the anode heat-load limitations.

An alternative solution for improving the density resolution consists in using contrast material and this method is widely employed in clinical routine.

Another promising approach to reach the absolute density measurement has been investigated by different groups in using a dual energy X-ray beam. For soft tissue, the C.T. number is proportional to electron density since compton interactions represent a very large amount of the total interactions. Due to photoelectric interactions, it is not the case for bone material. A dual energy data collection allows to separate these two contributions and the absolute density measurement can be reached both for soft tissue and for bone materials.

4.2. Spatial resolution

The spatial resolution in the transverse plane is presently limited by technological problems, but there is non fundamental reason which prevents future improvements.(4)

The expected advantages of a better spatial resolution are very important :

- An improvement for small size and high contrast structure imaging (internal ear structures for instance)
- A reduction of spark artefacts close to the high gradient structures, and consequently a better density resolution in these regions
- A lower expanding of the quantum noise due to the reconstruction process

The ideal detector should be in the millimeter range, typically 0.3 to 0.4 mm cell width, and the dead space should not exceed 20 % of the useful area. Such a detector supposes that new techniques for high density data collection could be simultaneously developed in order to reduce the complexity and the cost.

A first step can be expected with the conventional technologies for getting 20 pairs of lines per centimeter.

The spatial resolution along the longitudinal axis also requires to be improved. Major advantages can be expected :

- A better image quality for small structures with a high contrast
- A more accurate density resolution by reducing the partial volume effect
- A better image contrast for organ edge regions

Beam thickness of 1 to 1.5 mm can be used with the present machine but the useful photons fraction is then significantly reduced, and consequently, the exposure time increases in the same proportion with the already mentioned drawbacks.

The development of multi-line detectors will be a major advance in C.T. (4). So several slices (approximately 10) will be stored simultaneously with the same exposure time as for a present large thickness slice, and this method will provide a much better photons flux utilization. It is a very promising way in order to reach a true three dimensional imaging.

That three dimensional approach supposes that efforts can be invested in several fields :

- More powerful X-ray tubes since photons statistics will be the physical limitation of the image quality for each slice
- The development of multilinear array of detectors providing a good packing fraction (in order to minimize the dose to the patient) and a good rejection of scattered radiation. A stack of 10 to 12 linear arrays of one thousand cells each with 0.4 to 0.5 mm aperture seems to be a good tradeoff between the performances and the cost and complexity.
- The development of high density, fast and low cost data collection electroncis. Integrated technology seems to be a very promising way
- The development of fast digital process systems in order to reduce the reconstruction time since the image matrix size and the number of slices will be larger.

5 CONCLUSION

A competition is arising between C.T. and NMR in the field of medical diagnostic imaging, and it is clear that the medical community interest is presently focused on NMR imaging.

Nevertheless, it appears reasonable to assume that the clinical interest of C.T. for different pathologies is remaining. As long as this statement is confirmed, new technical advances can be expected in the near future in order to improve the main characteristics which are : the density resolution, the spatial resolution and the X-ray exposure time.

Since only the technological aspects are concerned in this paper, the major advances can be expected in the field of photons flux production and detection.

C.T. requires very stringent demands on X-ray tubes. Special tubes have already been developed for that application but further improvements are needed for high spatial resolution multislice machines.

Multilinear array of detectors seems to be the major technological advance to accomplish in the near future in order to significantly improve the image quality, and to reach a true three-dimensional imaging.

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