Proven Technology for the New 3D Complete-Body-Scan (3D-CBS) Medical Imaging Device

The International Commission for Radiation Protection (ICRP) and the U.S. National Council on Radiation Protection and Measurements (NCRP) recommends a limit of 100 mrem per year (average over five years) of exposure to ionizing radiation for the general population [1], [2]. A single PET (or CT) examination using devices currently available in hospitals gives the patient 10 to 20 times this dose.

The goal of the 3D-CBS is to reduce the radiation to the patient to 1/30 the radiation of current devices, bringing the dose to within the recommendations set by the ICRP, and **to improve the image quality**. An **acceptable radiation dose will permit annual screening for early detection of cancer** and other systemic anomalies, with the benefit of saving many lives.

Current PETs require a high radiation dose to the patients because they can capture only a few of the photons emitted from the patient's body: at most they can capture about two out of 10,000 photons emitted[1]. The sensitive area of the current detector that can capture photons (the axial field of view [FOV], or the length of the detector) covering the patient's body is very small and the electronics inefficient. Until now, the greatest impediment to extending the FOV has been the electronics of current PET, which could not efficiently capture the photons and was saturating with even the short FOV.

The unique architecture of the 3D-CBS electronics permits the extension, in a cost-effective manner, of the FOV to over one meter in length and captures about 1,000 out of 10,000 photons in time coincidence. **The innovations that reduce the required radiation to the patient** to 1/30 of current requirement lie partly in the way existing components (available off the shelf) are assembled together with the innovative section of the electronics (the 3D-Flow system). Such technology allows (see notes of Figure 1):

1. **an increase in the input bandwidth of the electronics from the 10 million events per second of current PET to over 36 billion in the 3D-CBS PET (a high bandwidth of the electronics is required because the photons arrive at the detector randomly). See Section 4 of [6];**
2. **an increase in the field of view to over one meter, providing good efficiency in photon detection (e.g. a 3D-CBS with only three times the FOV of current PET could detect nine times the number of photons compared to current PET when they are used in 3-D and 27 times when current PET are used in 2-D mode). See Figure 2; and**
3. **the accurate identification of most photons, using digital signal processing with neighboring data exchange performed by a set of DSPs on each electronic channel. Each DSP executes a complex real-time photon detection algorithm, described in Figure 34 of [6].**

This 3D-Flow architecture has been designed in IP form [3], suitable to be targeted to several technologies, and has been built into FPGA (2.6 million gates 0.18 micron CMOS technology, 8 aluminum layers) with four 3D-Flow processors in a single chip. Full simulations of the system with fault-tolerant capabilities have been performed for the entire system. A hardware prototype implementing these functions in real time, using Altera's FPGA (to be presented at the seminar at the Industrial Program of the IEEE Nuclear Science Symposium and Medical Imaging Conference at San Diego,CA, U.S.A., on November 6, 2001), proves its hardware feasibility. This hardware construction is the basic element of the project and is described in Figure 27 of [6]. Several of these basic elements replicated hundreds of times makes the electronic system of the 3D-CBS. The staging of the construction of the 3D-CBS is also presented in this document and in the more detailed document available at www.3d-computing.com/pb/3d-cbs.pdf.

[1] E.g., see the value display on the top frame of the latest model of the PET Advance Nxi by GE (or on the monitor of the latest model by CTI/Siemens). The display number between 20,000 to 35,000 counts per second is the number of pairs of photons in coincidence (true plus scattered) recorded by the PET device. This number is a small fraction of the over 350 million pairs of photons per second emitted by the patient's body as a result of the injection of about 10 mCi of radioisotope.

The first goal will be the construction of the 3D-CBS using off-the-shelf components and the current version of the 3D-Flow component in FPGA, which provides a system input bandwidth of the electronics of 10 billion events per second (instead of the current maximum 10 million events per second). This should make it possible to meet the goal of a radiation dose lower than the 100 mrem per year recommended by the ICRP. Further reduction in the radiation dose with the use of the 3D-Flow implemented in ASIC (which can provide an input bandwidth higher than 36 billion events per second) will further lower the radiation to the patient and will provide better images.

Table I shows the tradeoff between the cost of the non-recurrent engineering (NRE) and the cost and performance of the 3D-Flow component. The higher NRE cost of an advanced 0.12 µm CMOS technology provides a lower component cost, a higher processor speed, and lower power consumption; and it requires only two IBM PC chassis instead of six IBM PC chassis.

The risk involved in moving the current 3D-Flow technology in FPGA-PLD to a less expensive FPGA-hardcopy technology is zero, because it is implemented by the same company (Altera) that provides the FPGA. Their migration path from an FPGA-PLD programmable part to an FPGA-hardcopy component is tested on many other applications and is guaranteed at contract sign-off. This first step provides the largest cost reduction of the 3D-Flow processor of 60% to 90%.

The next step in the migration to an advanced 0.18 µm, (or 0.12 µm) CMOS technology, which makes use of a smaller cell as the basic element (a few transistors instead of several transistors, as a FPGA basic cell is made), better optimizes the use of the silicon area in the chip, and it provides better component yield. However, the NRE cost is higher because the application circuit (3D-Flow) requires a longer time and effort to be mapped and tested at the transistor level, while the FPGA needs to be mapped onto pre-existing circuits, which are already tested. The resulting cost of a 3D-Flow processing element (in an optimized circuit in a smaller silicon area with improved speed and lower power consumption) can go as low as $1/PE).

It is also possible to have a zero risk implementation of these migrations to technologies with more efficient use of the silicon by following a "signoff" procedure with the foundry manufacturing the component. The procedure provides that the manufacturer will assume full responsibility for obtaining working parts when the simulation passes tests that make use of the manufacturer's tools with the implementation of the geometry of the transistors implemented in the manufacturer's technology. After each of the above tests, a "signoff" takes place between the component manufacturer and the customer.

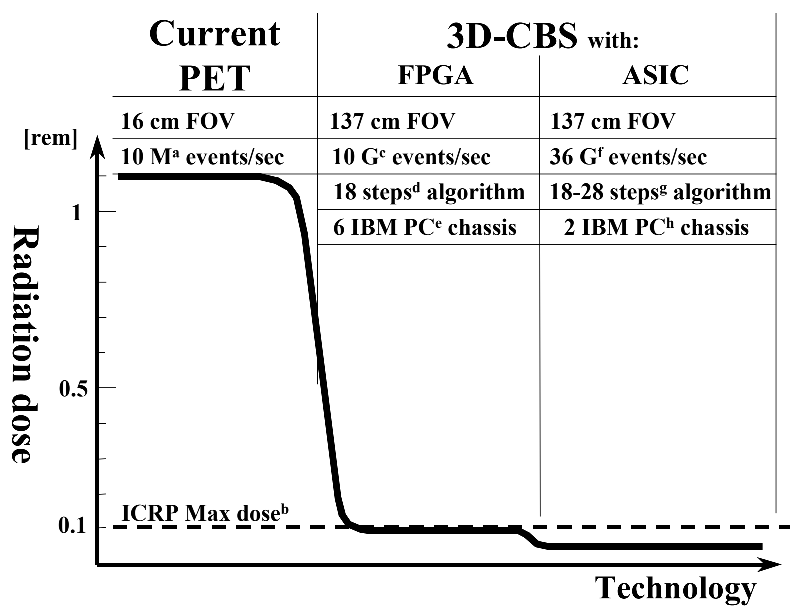

Figure 1. Roadmap of the construction of the 3D-CBS with different technologies.

[a]See references [4], and [5]
[b]See reference [1], [2].
[c]Calculated as 6 MHz input bandwidth of each 3D-Flow processor times 1792 electronic channels.
[d]The capability to execute an 18-step real-time algorithm (during each step, the 3D-Flow processor can execute up to 26 operations simultaneously) allows for accurately identifying the characteristics of the interaction between the incident photon and the detector. See Figure 34 of [6].
[e]Five IBM PC chassis contains 19 DAQ boards each, plus one chassis with 17 DAQ boards. A DAQ board is equipped with 16 channels with five sequentially implemented parallel-processing stages, implemented on 25 FPGAs. Each FPGA contains the functionality of 4 x 3D-Flow processors.
[f]Calculated as 20 MHz input bandwidth of each 3D-Flow processor, times 1792 electronic channels.
[g]See Figure 34 of [6]. The execution of a more sophisticated (longer than 18 steps) real-time algorithm allows capturing more photons and improving the quality of the images.
[h]Each IBM PC chassis contains 14 DAQ boards equipped with 64 channels on 25 ASICs, each with 16 x 3D-Flow processors.

TABLE I. TECHNOLOGY IMPLEMENTATION

Technology	Migration + NRE [$Million]	Risk	Cost per PE
FPGA-PLD	Done	done	note 1
FPGA-hardcopy	$0.15	zero	~$25
ASIC 0.18 µ	~$0.8	Manuf. Signoff	~$3
ASIC 0.12 µ	~$1.3	Manuf. Signoff	~$1

Note 1. The large FPGAs from Altera, Lucent Technologies and Xilixs cost form $2,000 to $4,000 during the first months, later the price drops when larger components become available.

For the purpose of understanding how the capturing of photons is greater than double when the FOV is doubled, let us assume that we simplify the representation of the detector as shown in Figure 2a and Figure 2b and assume the detector has only three rings of detector elements. We then consider only the LOR connecting opposite sets of detectors within the three rings instead of all possible LORs passing through the patient's body. We will call the top left detector elements A, B, C, and the detector elements on the bottom left of the figure D, E, F. For a linear source at the center of the FOV emitting pairs of photons in time coincidence in opposite directions, one could only capture three possible combinations AD, BE, and CF (See Figure 2a) when SEPTA are used (septa are lead rings between the ring-detectors that prevent photons arriving with an angle from hitting the detector). In the absence of SEPTA lead rings, there are nine possible combinations of pairs of photons: AD, AE, AF, BD, BE, BF, CD, CE, CF which can be captured (see Figure 2b).

If the FOV is doubled and we call the new elements at the top of the new detectors G, H, L, and the new elements at the bottom of the new detectors as M, N, P (see Figure 2c), then one could capture the following 36 combinations of pairs of photons emitted in opposite directions from a linear source in the center of the FOV. The possible pairs for which a LOR could be drawn are: AD, AE, AF, BD, BE, BF, CD, CE, CF, plus the new GM, GN, GP, HM, HN, HP, LM, LN, LP, plus the combination of old top and new bottom AM, AN, AP, BM, BN, BP, CM, CN, CP, plus the combination of the new top and the old bottom GD, GE, GF, HD, HE, HF, LD, LE, LF.

Considering that most of the PET (even the most advanced) available currently in hospitals use a 2-D mode for the torso, where only the combinations AD, BF, and CF are detected[2], the difference between the

[2]Pairs of photons with a direction hitting detectors elements located on different rings cannot be detected because of the presence of the SEPTA between rings and because of the electronics, which does not have a set of DSPs for each channel with the capability of reconstructing the energy from the neighboring channels and measuring accurately the depth of interaction. Some of the current PETs for the head are used in 3-D mode (without septa, thus accepting the arrival of pair of photons with an angle from adjacent

current PET and the 3D-CBS when the FOV is doubled, is from 6 times to 36 times. If the FOV of the current PET is tripled from 16 cm to 48 cm, then the difference in captured pairs of photons will increase from 9 to 81 times when using the 3D-CBS approach.

Although pairs of photons having a direction with an angle greater than 45 degrees are not detected because of the constraints set by the time-window and because of the higher attenuation introduced by more tissue, the increase of FOV in the 3D-CBS from 16 cm in the current PET to over one meter, provides an increase in detected photons for each location of the body along the torso and head, which is much greater than the increase in the FOV. (See Figure 2)

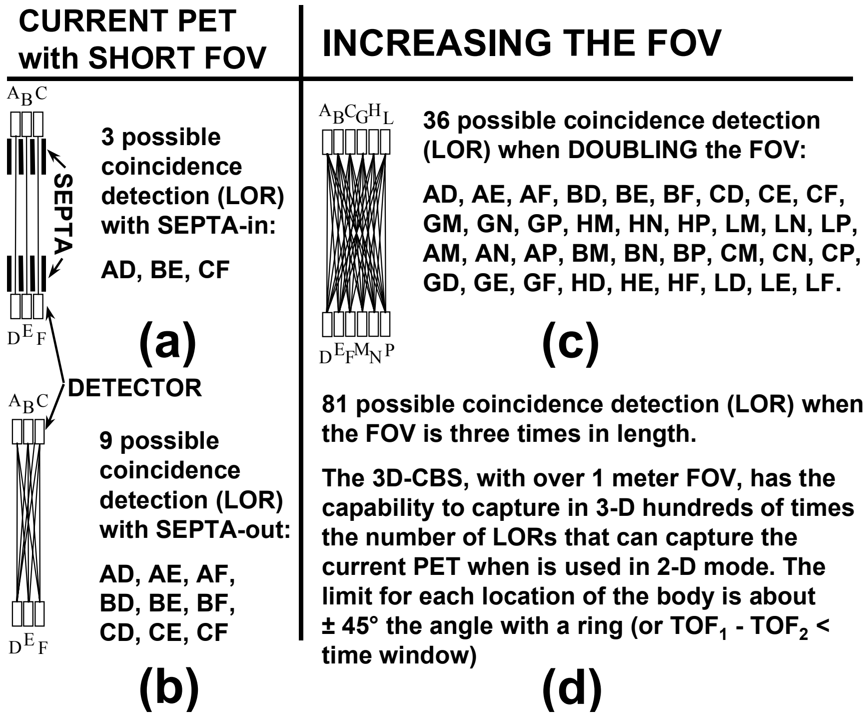

Figure 2. A PET with an axial FOV that is twice as long as the short FOV of the current PET can detect four times the number of photons in time coincidence from an organ emitting photons from the center of FOV. Section (a): Example of the limited detection of back-to-back photons used in current PET when torso or whole-body scans are performed. (b): For the same short FOV, the number of photons captured increase from 3 to 9 when the SEPTA are removed. (c): Doubling the axial FOV increases the Lines of Response (LOR) four times (or 13 times if compared to 2-D mode). (d): When the FOV is increased three times, the number of pairs of photons that can be captured increases 81 times (or 243 times if compared to the current use of the PET in 2-D).

[1] ICRP Publication 60, Annuals of the ICRP 21, pp. 25; 1991.
[2] Ordonnance sur la radioprotection (OraP) Le conseil federal suisse. 19 decembre 2000.
[3] Crosetto, D.: LHCb base-line level-0 trigger 3D-Flow implementation. Nuclear Instruments and Methods in Physics Research, Section A, vol. 436 (Nov. 1999) pp. 341-385.
[4] Phelps, M.E., et al., The Changing of Positron Imaging System. Clinical Positron Imaging, vol. 1(1): 31045, 1998.
[5] Jones, W.F. et al.: "Next generation PET data acquisition architectures," IEEE TNS, vol. NS-44, pp. 1202, (1997).
[6] Crosetto, D. "Saving lives through early cancer detection: Breaking the current PET efficiency barrier with the 3D-CBS". www.3d-computing.com/pb/3d-cbs.pdf.

rings). However, as the scattering increases with the increase of the volume of the body, such is the case with the torso, there is a need of a more efficient electronics such as the one used in the 3D-CBS.