Note that the reduction in scan time (therefore, the increase in volume coverage speed) follows an exponential relationship over time. The slope of the fitted line is roughly 1.34/year. This graph states that on average the scan time per slice has been reduced by a factor of 1.34 per year over the last 30 years!

1.3 Different Generations of CT Scanners

In the previous section, we presented a brief review of CT history. In this section, we provide a general overview of the evolution of CT technology over the last 30 years. Because of the nature of the overview, detailed comparisons between the pros and cons of different types of scanners are omitted. We will provide more in-depth coverage on this subject in later sections of the book wherever appropriate. For example, many discussions can be found in Chapter 6 as part of the image artifact analysis.

The type of scanner built by EMI in 1971 is called the first-generation CT. In a first-generation scanner only one pencil beam is measured at a time. In the original EMI head scanner, the x-ray source was collimated to a narrow beam 3-mm wide (along the scanning plane) and 13-mm long (across the scanning plane). The x-ray source and detector were linearly translated to acquire individual measurement. The original scanner collected 160 measurements across the scan field. After the completion of the linear measurements, both the x-ray tube and the detector rotated 1 deg to the next angular position to acquire the next set of measurements, as shown in Fig. 1.12.

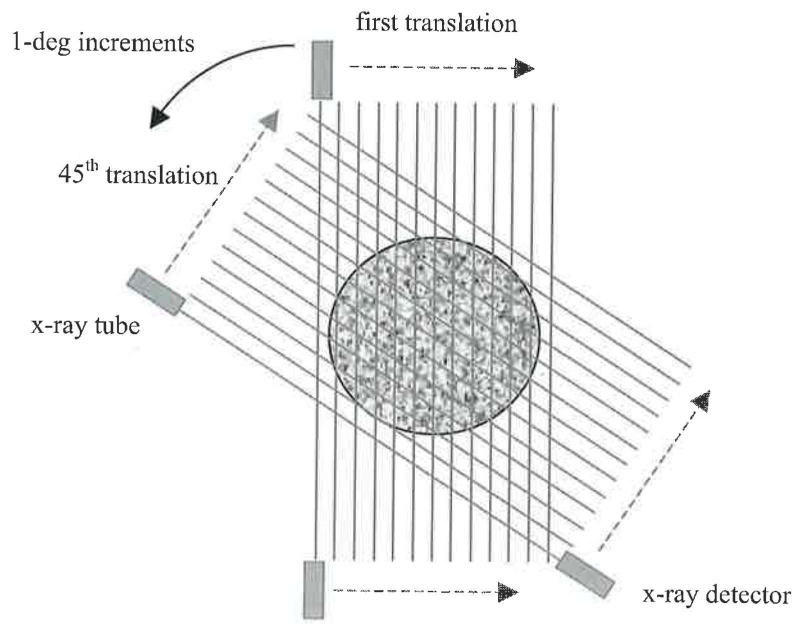

Figure 1.12 First-generation CT scanner geometry. At any instant, a single measurement is collected. The x-ray tube and detector translate linearly to cover the entire object. The entire apparatus then rotates 1 deg to repeat the scan.

Although results from clinical evaluations of the first-generation scanners were promising, there remained a serious image quality issue associated with patient motion during the 4½ minutes of data acquisition.[18] The data acquisition time had to be reduced. This led to the development of the second-generation scanner illustrated in Fig. 1.13. Although this is still a translation-rotation scanner, the number of rotation steps is reduced by the use of multiple pencil beams. In the figure, we depict a design in which six detector modules are used. The angle between the pencil beams is 1 deg. Therefore, for each translation scan, we acquire projections from six different angles. This allows the x-ray tube and detector to rotate 6 deg at a time for data acquisition, representing a reduction factor of 6 in the acquisition time. In late 1975, EMI introduced a 30-detector scanner capable of acquiring a complete scan in less than 20 sec.[6] This was an important milestone for body scanning because the scan interval fell within the breath-hold range for most patients.

One of the most popular scanner types is the third-generation CT illustrated in Fig. 1.14. In this configuration, a large number of detectors are located on an arc concentric to the x-ray source. The size of the detector is sufficiently large so that the entire object is within the detector field of view at all times. The x-ray source and the detector remain stationary with respect to each other while the entire apparatus rotates about the patient. Linear motion is eliminated to significantly reduce the data acquisition time.

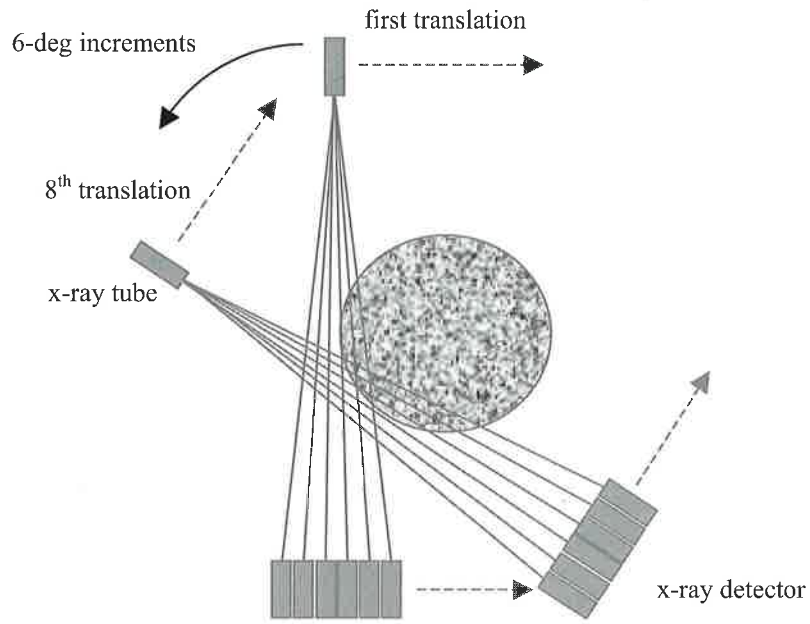

Figure 1.13 Second-generation CT scanner geometry. At each instant, measurements from 6 different angles are collected. Although the x-ray source and detector still need to be linearly translated, the x-ray tube and detector can rotate every 6 deg.

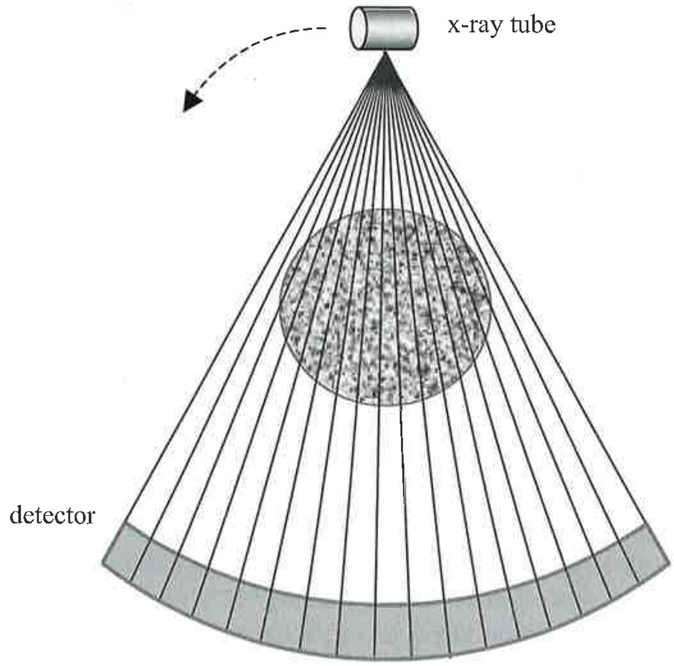

Figure 1.14 Third-generation CT scanner geometry. At any instant, the entire object is irradiated by the x-ray source. The x-ray tube and detector are stationary with respect to each other while the entire apparatus rotates about the patient.

In the early models of the third-generation scanners, both the x-ray tube power and the detector signals are transmitted by cables. Limitations on the length of the cables force the gantry to rotate both clockwise and counterclockwise to acquire adjacent slices. The acceleration and deceleration of the gantry, which typically weighs several hundred pounds, restrict the scan speed to roughly 2 sec per rotation. Later models use slip rings for power and data transmission. Since the gantry can rotates at constant speed during successive scans, scan time is reduced to 0.5 sec or less. The introduction of the slip ring technology was also a key to the success of helical or spiral CT (a separate chapter is devoted to this topic). Because of the inherent advantages of the third-generation technology, nearly all of the state-of-the-art scanners on the market today are third generation.

Several potential technology challenges in the design of third-generation CT, such as detector stability and aliasing, led to the investigation of the fourth-generation concept, as depicted in Fig. 1.15. In this design, the detector forms an enclosed ring and remains stationary during the entire scan, while the x-ray tube rotates about the patient. Unlike the third-generation scanner, a projection is formed with signals measured on a single detector, as the x-ray beam sweeps across the object. The projection, therefore, forms a fan with its apex at the detector, as shown by the shaded area in Fig. 1.15. (A projection in a third-generation scanner forms a fan, with the x-ray source as its apex.) One of the advantages of the

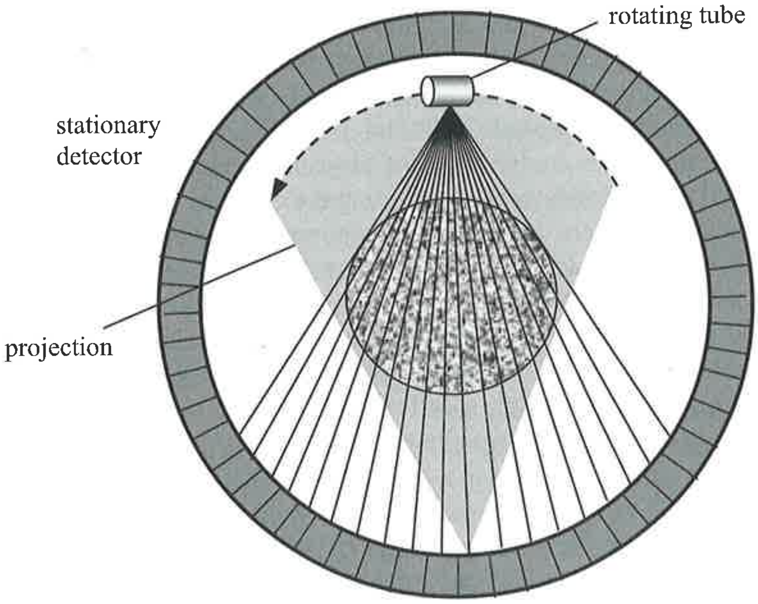

Figure 1.15 Geometry of a fourth-generation CT scanner. At any instant, the x-ray source irradiates the detectors in a fan-shaped x-ray beam, as shown by the solid lines. A projection is formed, however, with the collection of measurement samples of a single detector over time, as depicted by the shaded fan region.

fourth-generation scanner is the fact that the spacing between adjacent samples in a projection is determined solely by the rate at which the measurements are taken. This is in contrast to the third-generation scanning, in which the sample spacing is determined by the detector cell size. Higher sampling density can eliminate potential aliasing artifacts. In addition, because each detector cell is exposed directly to the x-ray source without any attenuation at some point during each rotation, the detector can be recalibrated dynamically during the scan. This significantly reduces the requirements on the stability of the detector.

A potential drawback of the fourth-generation design is the scattered radiation. Because each detector cell has to receive x-ray photons over a wide angle, no effective and practical scatter rejection can be performed by postpatient collimator. Although other scatter correction schemes, such as the use of a set of reference detectors or software algorithms, are useful, the complexity of correction is likely to increase significantly with the introduction of multislice or volumetric CT.

A more difficult drawback to overcome is the number of detectors required to form the complete ring. Because the detector has to surround the patient at a large circumference (to maintain an acceptable source-to-patient distance), the number of detector elements and the associated data acquisition electronics become quite large. For example, a recent single-slice fourth-generation scanner requires 4800 detectors. The number would be much higher for multislice scanners. For economic and practical reasons, fourth-generation scanners are likely to be phased out.[6]

The electron-beam scanner, sometimes called the fifth-generation scanner, EBCT, or EBT, was built between 1980 and 1984 for cardiac applications.[19] To "freeze" cardiac motion, a complete set of projections must be collected within 20 to 50 msec. This is clearly very challenging for conventional third- or fourth-generation types of scanners, because of the enormous gravitational force placed on the x-ray tube and the detector. In the electron-beam scanner, the rotation of the source is provided by the sweeping motion of the electron beam (instead of the mechanical motion of the x-ray tube). Figure 1.16 shows a simplified schematic diagram of an electron-beam scanner. The bottom arc (210 deg) represents an anode with multiple target tracks. A high-speed electron beam is focused and deflected by carefully designed coils to sweep along the target ring, similar to a cathode ray tube. The entire assembly is sealed in a vacuum. Fan-shaped x-ray beams are produced and collimated to a set of detectors, represented by the top arc of 216 deg. The detector ring and the target ring are offset (noncoplanar) to make room for the overlapped portion. When multiple target tracks and detector rings are used, coverage of 8 cm along the patient long axis can be obtained for the heart. Since there is no mechanical moving part in the system, scan time as fast as 50 msec can be achieved. For noise considerations, however, multiple scans are often averaged to produce the final image. A more complete description of the electron beam scanner can be found in Ref. 20.

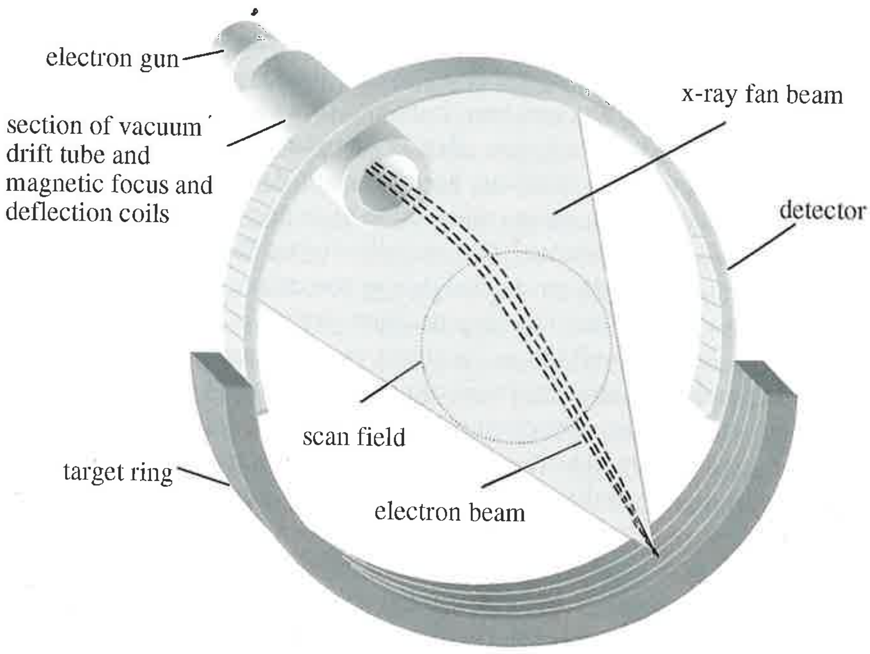

Figure 1.16 Geometry of electron beam scanner.