1. Introduction
Toshiba Electron Tubes & Devices Co., Ltd. (TETD) introduced Japan's first X-ray tube in 1915. Since then, by cultivating and expanding our core competence, we have been engaged in the development, manufacture, and sale of products with advanced performance and high reliability. In 2015, we are celebrating 100 years in business.

This report describes the operating principles of the X-ray tube, I.I., and FPD, which are our major products in the healthcare field, as well as the features they require, the main technologies unique to such products, and our future prospects.

2. Diagnostic X-ray tube
2.1 Principle of operation
An X-ray tube is a vacuum tube that produces X-rays by causing electrons to collide with an anode (target) in a vacuum (Figure 1). An X-ray tube assembly is an X-ray tube contained in a tube housing that has electrical and mechanical safety mechanisms, X-ray protection mechanisms, and an interface with diagnostic equipment. We have developed a wide range of X-ray tubes suitable for a variety of purposes (Figure 2).

2.2 Required features
In addition to X-ray output, which is their fundamental function, the following features are required for diagnostic X-ray tubes:
(1) Focal spot design that ensures high image quality
(2) Stable operation during examinations
(3) Quiet operation to minimize stress on patient and X-ray Devices Contributing to Sophistication of X-ray Diagnostic Systems

X-ray tubes to generate X-rays, as well as X-ray image intensifiers (I. Is) and X-ray flat panel detectors (FPDs) to convert X-ray images into electronic signals, are key devices in X-ray diagnostic systems, which are playing a major role in the advancement of diagnosis and treatment.

Toshiba Electron Tubes & Devices Co., Ltd. (TETD) has been offering optimal products incorporating the most advanced technologies to customers through continuous technological innovations. These include a high-sensitivity technology for X-ray I. Is and X-ray FPDs to suppress patient exposure doses, a focal spot design technology for X-ray tubes and high-resolution technologies for X-ray I. Is and X-ray FPDs that enhance image quality and make it possible to detect smaller lesion areas, and a noise reduction technology for X-ray tubes to realize a comfortable medical environment with reduced stress on both patients and medical staff.
physician
(4) Reduced burden on the environment.

2.3 Main technologies
We employ the following technologies to meet the requirements of diagnostic X-ray tubes:
(1) Optimized focal spot design using simulation technologies
By ensuring uniform density of the electron beam directed at the target, it is possible not only to improve image quality but also to minimize generation of X-rays that do not contribute to image creation, thus reducing the patient’s X-ray exposure. To develop an optimized focal spot design, we have been making full use of simulation technologies that take electron density into consideration (Figure 3).
(2) Ensuring stable operation by suppressing anode temperature
In rotating anode X-ray tubes employing conventional ball bearings, anode cooling is limited to thermal radiation, because the rotating section and the fixed support shaft are insulated by the bearings. On the other hand, for a liquid metal hydrodynamic bearing (LM bearing) employing a gallium alloy (which is liquid at room temperature) as a lubricant, because the rotating section is thermally in contact with the fixed support shaft via the liquid metal, it is possible to improve the anode cooling efficiency by conduction cooling, which makes it easier to lower the anode temperature than is possible with ball bearings. As a result, more stable operation is ensured.
We have also been actively developing X-ray tubes with a compact anode by employing conduction cooling of the LM bearing. Development of a smaller anode facilitates design of more compact X-ray tubes, allowing improved ease of installation of such X-ray tubes in medical equipment.
(3) Quiet operation with LM bearings
Although ball bearings are generally used for the rotation mechanism of rotating-anode X-ray tubes, we employ LM bearings in X-ray tubes for X-ray angiography systems and X-ray computed tomography (CT) scanners that require a large anode. As the LM bearing is not directly in contact with the rotating section, very quiet operation is achieved.
(4) Oil-free X-ray tube assembly
We have commercialized an oil-free X-ray tube assembly in which no insulating oil is used as a coolant (Figure 4). The oil-free X-ray tube assembly is water-cooled, making it possible not only to improve the cooling capability but also to reduce the burden on the environment, and we have therefore been developing a range of these products.

2.4 Future prospects
We will continue to develop advanced X-ray tube assemblies suitable for diagnostic equipment as it con-
continues to evolve, and endeavor to further improve our product quality in order to support secure and comfortable healthcare.

3. I.I.

3.1 Principle of operation

An I.I. is a vacuum tube device that converts invisible X-ray image sources to visible light sources, allowing observation of dynamic X-ray images. In addition, an I.I. product combined with a TV camera that permits such image sources to be output as image signals is called an I.I. system (Figure 5).

Recently, FPD products have become available as devices for detecting X-rays. However, I.I.s are still suitable when high cost performance is required (e.g., in emerging markets) or when quick response is essential. Our I.I. products are appreciated for their performance, quality, and availability, and have been sold in many countries and regions of the world.

An I.I. is a vacuum tube which incorporates an input surface (consisting of a cesium iodide (CsI) scintillator and a photoelectric surface), a focusing electrode, and an output surface. It converts X-rays into visible light in the following three steps:

1. Incident X-rays are converted into weak visible light by the CsI scintillator.
2. The visible light is converted into electrons at the photoelectric surface and emitted inside the vacuum tube.
3. The emitted electrons are accelerated and focused by electrodes, which act as an electron lens, onto the output screen, and converted into bright visible light. The acceleration and focusing of electrons in this way permits output of bright dynamic images that can be captured by a TV camera (Figure 6).

3.2 Required features

In clinical practice, there is demand for an I.I. capable of higher resolution combined with a TV camera with higher pixel resolution for improved detail in fluoroscopic images; and for an I.I. with higher sensitivity (more efficient use of X-rays) in order to reduce the patient’s X-ray exposure. In emerging markets, there is demand for TV cameras that can be connected to the LAN connector of a PC in standard configuration (GigE camera) in order to easily display images.

3.3 Main technologies

An I.I. detects X-ray photons individually, and after an amplification process, displays them as an image consisting of an array of dots. Therefore, the number of detected X-ray photons is important. In order to obtain a clear image, it is necessary to efficiently convert the X-ray photons to provide an image consisting of as many dots as possible. X-rays have strong penetrating power and may penetrate the CsI scintillator. To prevent this, the thickness of the scintillator layer is increased to improve efficiency. However, simply thickening the scintillator layer increases the distance between the point at which the visible light is emitted at various angles and the photoelectric surface, which results in lower resolution.

In order to address this problem, the scintillator is composed of columnar crystals perpendicular to the input surface (Figure 7). The visible light is guided to the photoelectric surface by reflection within the columnar crystals, minimizing its spread. As a result, high-resolution images can be obtained with high efficiency. In practice, we use our proprietary technologies to control conditions during layer creation so that the optimal column diameter and separation between the columnar crystals can be obtained.

We also use unique photoelectric surface-forming technologies to provide high sensitivity and scintillator layer-forming technologies (e.g., output surface scintillator) for displaying high-definition images, ensuring high performance and quality in our I.I. products.

In order to incorporate an I.I. in a medical device, a TV camera system is required. To fully benefit from the
performance of the I.I., a dedicated TV camera must be prepared. Because the image output from the I.I. is circular, square charged-coupled devices (CCDs) rather than conventional rectangular CCDs are used as image sensors for the camera. In addition, a high signal-to-noise ratio for monochrome images is required. In the conventional method, a camera control unit (CCU) was used for various types of image processing and a capture board was installed in a PC to import signals. It was therefore necessary to prepare many dedicated devices other than the I.I. to obtain images.

To address this issue, we have developed a GigE camera that permits the output from the I.I. dedicated TV camera to be directly input to a normal PC. It is possible to establish a TV camera system by directly connecting this camera to a PC without a CCU or capture board. This is useful for establishing simplified systems and will be particularly suitable in emerging markets.

3.4 Future prospects

Image intensifiers have a long history, and as analog devices these products reflect many technologies. By utilizing digital devices like the GigE camera, we will continue developing I.I.s as an X-ray image display device that can be accepted in emerging markets.

4. FPD

4.1 Principle of operation

A FPD is a thin and flat solid sensor that converts X-ray image sources transmitted through the human body into digital signals at the X-ray conversion module to produce the image (Figure 8). In developing an FPD, we employed an indirect conversion method using a CsI scintillator and a photodiode (PD) array. We utilized the CsI scintillator-forming technologies and skills that had been developed and improved for our I.I. products. The principle of operation of the FPD is described below.

The X-ray image sources input to the FPD are converted into visible light by a CsI scintillator. The visible light is then converted into electric charge at the PD provided for each pixel and these signals are stored in the capacitance section of the PD. The signals are read out through the thin-film transistor (TFT) switch provided for each pixel and amplified by a low-noise amplifier, undergoing analog-digital conversion to become digital video signals (Figure 9).

4.2 Required features

The following two major features are required for FPDs:

1. Higher X-ray sensitivity by improving the efficiency of conversion from X-rays to electric charge in order to minimize the patient’s exposure to X-rays
2. Higher resolution in order to detect smaller lesions

In FPDs, there is generally a trade-off between higher sensitivity and higher resolution.
4.3 Main technology “Quadcel”

In our FPDs, we have succeeded in reducing the trade-off between these features by employing the newly developed “Quadcel” technology. Specifically, Quadcel consists of the following four core technologies:

1. High-resolution and high-sensitivity CsI-forming technology
2. CsI scintillator direct vapor deposition technology
3. High-reflection coating technology
4. Highly moisture-proof sealing technology.

Details of these four technologies are described below:

1. High-resolution and high-sensitivity CsI-forming technology
   
   We have succeeded in developing a flat scintillator layer consisting of columnar crystals with a fine diameter (5 μm) and high degree of independence from each other, even though the columnar crystal layer is thick (600 μm) (Figure 10). The figure shows independent but narrowly separated columnar crystals. These features make it possible to ensure both high resolution and high sensitivity despite the thickness of the layer.

2. CsI scintillator direct vapor deposition technology
   
   Generally, the CsI scintillator layer used for FPDs is formed independently of the PD and stacked later. For this method, however, a stack layer is generated between the scintillator layer and PD (adhesive and/or micro space), which causes light scattering at the stack layer, resulting in reduced resolution. On the other hand, we have employed a unique layer-forming technology which has made it possible to directly evaporate CsI scintillators onto the PD. This eliminates light scattering between the PD and CsI, ensuring both high sensitivity and high resolution.

3. High-reflection coating technology
   
   Since visible light converted within the CsI scintillator is transmitted in a radial pattern within the crystals of the CsI scintillator, half of the emitted light is transmitted away from the PD and not effectively used. By reflecting this light at the top of the scintillator layer, the amount of light received at the PD can be increased. However, it is necessary to accurately return the generated light to the same columnar crystal, because failure to do so causes dispersion of the light, resulting in reduced resolution. We have therefore developed a material and a structure that do not allow the light from a CsI scintillator crystal to diffuse to any other crystal and that reflects such light at a high efficiency. This technology made it possible to efficiently improve the amount of light received at the PD while maintaining the resolution. As a result, sensitivity was improved by approximately 80% compared to FPDs without the reflecting material.

4. Highly moisture-proof sealing technology
   
   CsI scintillators are sensitive to humidity. Specifically, if the CsI scintillator is exposed to moisture, deliquescence occurs and the columnar crystals collapse, resulting in reduced resolution. In order to ensure that FPDs have high reliability and long service life, it is important to provide a protective structure against external environmental factors such as moisture. Generally, moisture-proof resin sealing is applied as a protective structure, but its moisture-proof performance may be insufficient. For higher reliability, we have therefore employed a highly airtight moisture-proof structure. The sealing material used is a metal foil with low X-ray attenuation. These features ensure higher reliability of our FPDs than those employing resin sealing.

With the Quadcel technology described above, we have succeeded in ensuring high sensitivity while providing high resolution (Figure 11).
4.4 Future prospects

With low-dose exposure and high image quality, our FPDs are highly appreciated by customers around the world.

In order to encourage development of diagnostic imaging devices and contribute to the advancement of healthcare, we will continue to promote technological innovation.

5. Conclusion

Due to the excellent features and reliability of our products, the X-ray tube assemblies, I.I.s, and FPDs we have developed are highly evaluated by customers both in and outside Japan.

We will continue to produce technological innovations, releasing industry-leading products that will further contribute to safe and comfortable healthcare.