inCiTe™
3D X-ray Microscope

TECHNICAL NOTE

INTRODUCTION TO PHASE-CONTRAST MICRO-COMPUTED TOMOGRAPHY

WHAT IS MICRO-COMPUTED **TOMOGRAPHY?**

When an object is placed between an X-ray source and a detector, the shadows (or *projections*) of the object are captured by the detector. Computed tomography, also known as CT, is the process of reconstructing a 3D image representation of the object from its X-ray projections using computer algorithms. The source-object distance (SOD) and source-detector distance (SDD) are two important physical parameters in the design of a micro-CT scanner as they affect magnification of the object, throughput of the system, and the field of view.

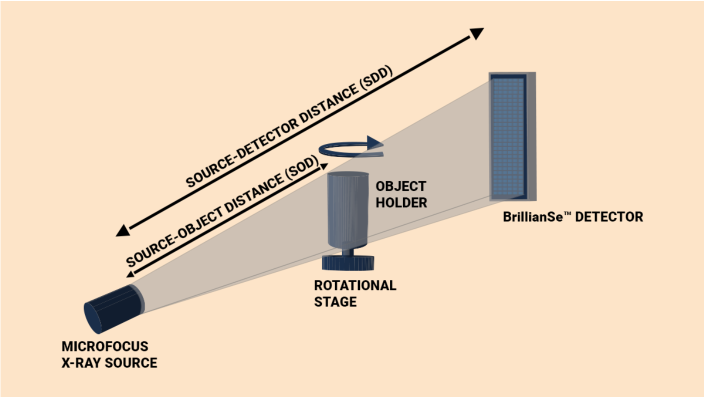


Figure 1: Illustration of a micro-CT scanner

TYPICAL MICRO-CT **PARAMETERS**

Micro-CT systems come in all shapes and sizes—depending on the applications. However, there are some basic parameters that can quickly tell both designers and users the performance of a micro-CT scanner.

Spatial Resolution

Spatial resolution is commonly reffered to as *image resolution*. It refers to how close images features can be to each other while still be distinguishable. There are different ways to quantify spatial resolution; one convenient and modern way is through the modulation transfer function (MTF).

Modulation Transfer Function

The modulation quantifies the relative amount the detected signal amplitude stands out from the background. This is a measure of image contrast. If we express how the contrast depends on feature size, we get a measure of spatial resolution. The MTF does exactly that by expressing the modulation as a function of spatial frequency.

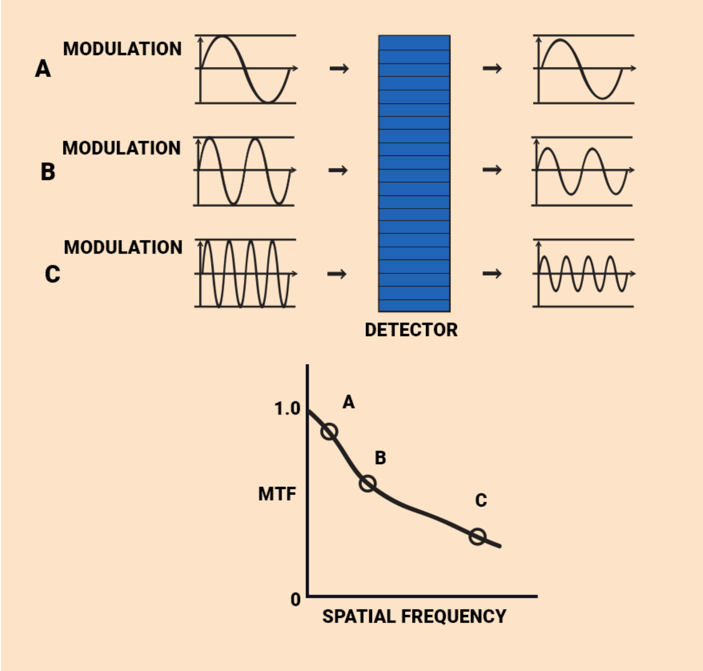


Figure 2: MTF, Measure of contrast capability as a function of spatial frequency[1].

[1] Even though the image is not an actual sine wave, it can be decomposed mathematically into sine and cosine components using the Fourier Transform. Thus, MTF is expressed in terms of attenuations of an image's spatial sinusoidal components.

Modulation Transfer Function CONTINUED

Higher spatial frequencies correspond to smaller objects. As spatial frequency increases, the detector has an increasing difficulty in reproducing the small features in the detected image because of inherent blurring present in the detector. The MTF is equal to one (i.e., perfect contrast) at zero spatial frequency because it represents the background. By the definition of the modulation, all non-zero spatial frequencies are expressed relative to the background and in practice are less than one. The limit of spatial resolution is often defined by an MTF of 0.1 (10% of background).

Detective Quantum Efficiency

Our perception of features in an image is also affected by *image noise*. To take this into account, the detective quantum efficiency (DQE) quantifies the signal-to-noise ratio transfer (SNR) in a detector. The best SNR possible is the intrinsic photon SNR in the incident beam. The DQE reports the SNR in the acquired image, relative to this photon SNR. As such, an ideal detector has a DQE of one (i.e., no additional noise added through detection). The value of the DQE depends on the spatial frequency, or feature size, being considered. Because the MTF (signal) tends to decrease with increasing spatial frequency, the DQE will as well.

Voxel Resolution

Also typically referred to as nominal resolution, this is the smallest possible volume element (i.e. 3D pixel) in the reconstructed volume. It is not a measure of spatial resolution, as features of that size may not actually be distinguishable in the (2D) image. The amount of available magnification will affect the nominal resolution.

Detectability

Detectability refers to the smallest feature that can be represented by a voxel. Again, this is not a measure of spatial resolution (e.g., the feature size may be smaller than the voxel itself). Detectability is related not only to the voxel resolution, but also to the X-ray absorption of the material and the signal-to-noise ratio of the detector itself. As such, detectability will vary according to the type of material being imaged. Furthermore, a detector with sufficient contrast compared to background noise will produce better detectability.

X-RAY DETECTION TECHNIQUE **INDIRECT VS. DIRECT**

Digital X-ray detectors can be classified based on either direct or indirect conversion techniques. In either case, the digital image readout can be done through: crystalline Si (c-Si) charge-coupled device (CCD), amorphous silicon (a-Si) thin-film transistor (TFT), or c-Si complementary metal-oxide-semiconductor (CMOS). CCD detectors are capable of real-time frame rates (i.e., 30 frames per second) with relatively low noise and a small pixel size, but are limited in imaging area. The a-Si detectors can be fabricated over large area which is required for full-field clinical radiology. Nevertheless, a-Si detectors inherently suffer from higher noise and have a large pixel size (>50 μm). CMOS imaging technology has emerged as a competitor to CCD detectors with comparably low noise, a similar scalability to very small pixel sizes, and higher frame rates. It is also compatible with standard CMOS processing allowing high levels of integration.

Indirect Conversion

In indirect conversion, either a pixel-level a-Si/CMOS photodiode or CCD potential well is used to collect optical light generated by a scintillator such as CsI or Gd_2O_2S. Conventional high spatial resolution scintillator-based detectors have poor absorption efficiency at high spatial resolutions due to thinning of the scintillator to minimize secondary optical scatter.

Direct Conversion

In direct conversion, the thickness of the photoconductor does not affect the spread of absorbed energy from X-ray interactions, and the subsequent diffusion of photo-generated charge carriers during transportation is negligible. No significant degradation of spatial resolution occurs as the photoconductor thickness is increased for high-energy applications. Nevertheless, the fabrication process for direct-conversion detectors has many technical challenges. Therefore, indirect conversion remains the standard method of X-ray detection in commercial CT systems.

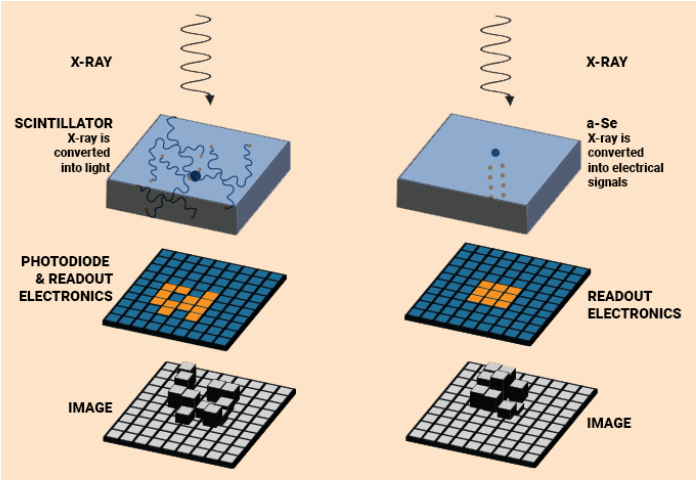


Figure 3: Indirect (L) and direct (R) X-ray detection. Note that indirect conversion requires a scintillator to convert X-ray visible light.

FACTORS AFFECTING **MICRO-CT RESOLUTION**

Pixel size is not everything. Having a small pixel size is intuitively a criterion to achieve high resolution. However, achieving good contrast relative to noise is the key in micro-CT imaging, which is expressed through metrics such as MTF and DQE. This enables us to distinguish small volumetric features and discriminate different materials. There are other components besides the detector in micro-CT that can greatly influence the resolution as well.

X-RAY SOURCE FOCAL POINT AND **OBJECT PLACEMENT**

As shown in Figure 4, if the size of the X-ray source focal spot is nearly a perfect point source, then there would be very little penumbra (unsharpness in the X-ray shadow). In this case, the physical pixel size of the detector gives us the resolution limit, regardless of object position.

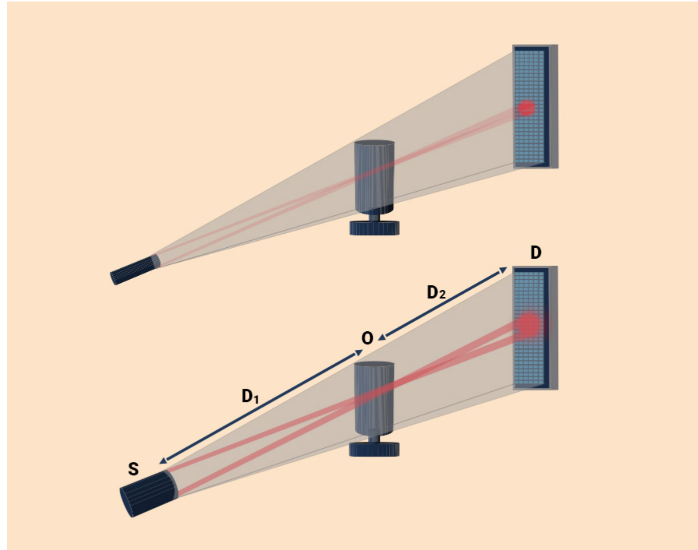


Figure 4: Effect of the object position on spatial resolution

In reality, the spatial resolution of an X-ray source is limited by the focal spot size σ_f that is not a perfect point. Through geometric magnification in the cone-beam imaging geometry, the detected focal spot size will be magnified: $\sigma_f(M-1)$, where $M=(D_1+D_2)/D_1$, is a factor determined by the source-to-object (S-to-O) distance D_1 and object-to-detector (O-to-D) distance D_2. The increase in penumbra results in increased geometric unsharpness in the object image. The equivalent blurring introduced to the object is $\sigma_g= \sigma_f(M-1)/M$. When the object is moved very close to the source, the blurring is solely dependent on focal spot size of σ_f, while it is not at all dependent when the object is close to the detector.

The micro-CT X-ray source, detector, and geometric magnification can be optimized such that the system resolution is simultaneously higher than both the detector and X-ray source spatial resolution. Depending on the size of the pixel and the size of the spot, however, the system may be limited by either detector or X-ray source.

BENEFITS OF PHASE CONTRAST **FOR MICRO-CT**

The primary advantage of the phase-contrast paradigm is that when an object presents poor conventional absorption-contrast (e.g. soft biological tissue or other low-density materials such as polymers), contrast can instead be generated with higher sensitivity using a variety of phase-contrast techniques. The major requirement is the ability to translate phase information to image contrast.

BENEFITS OF PHASE CONTRAST **FOR MICRO-CT** CONTINUED

Traditionally, the conventional X-ray detector measures only X-ray intensity. To capture the phase information, specialized optical elements need to be added in order to convert the phase shifts into intensity. The use of grating interferometers is an example used in commercial phase contrast micro-CT. A more straightforward implementation is to produce phase-contrast through simple free-space propagation. Free-space propagation renders phase variations in the X-ray wavefront at the object as intensity fluctuations at the detector. This is done by resolving the interferences of the refracted object beam with the unaltered beam.

The only requirement for propagation-based phase-contrast is a high-resolution detector and large enough transverse spatial coherence length l_t, given by $l_t = \lambda D_1 / \sigma_f$ where λ is the X-ray wavelength. A microfocus source should be used to achieve this if source-to-object distance D_1 is physically constrained, also for efficiency due to the inverse square fall off of X-ray flux.

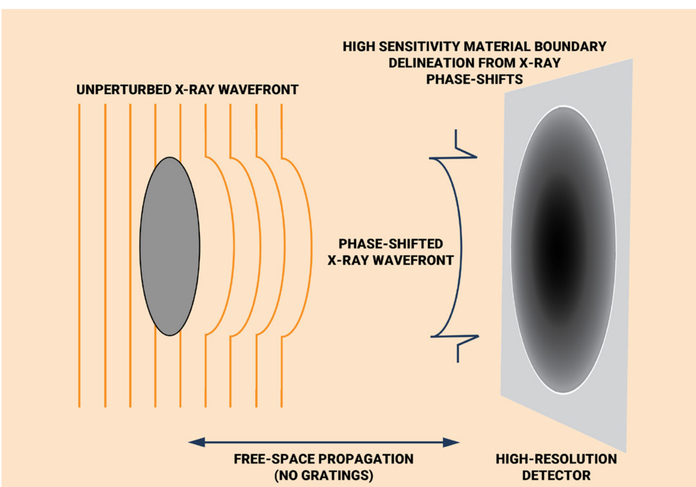
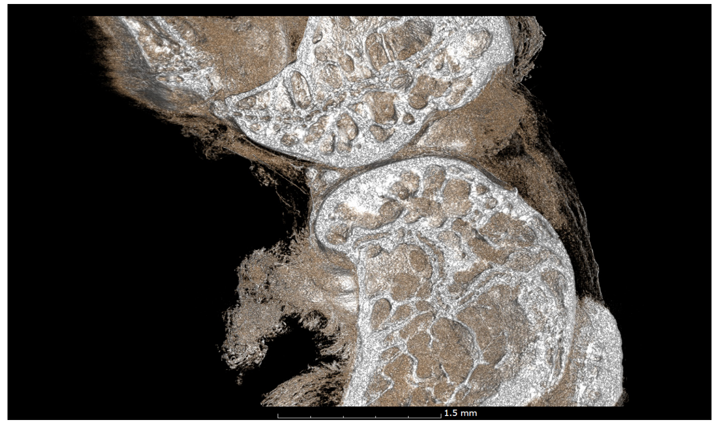


Figure 5: Propagation-based, grating-less phase-contrast

MICRO-CT **APPLICATIONS**

CT systems are commonly used in hospitals as a medical imaging diagnostic tool. Micro-CT scanners can also have medical applications, but are by no means limited to it. The applications of micro-CT scanners can typically be classified into the following areas.

Life Science



Sample: 3D Mouse knee (3D rendering)

Material Analysis

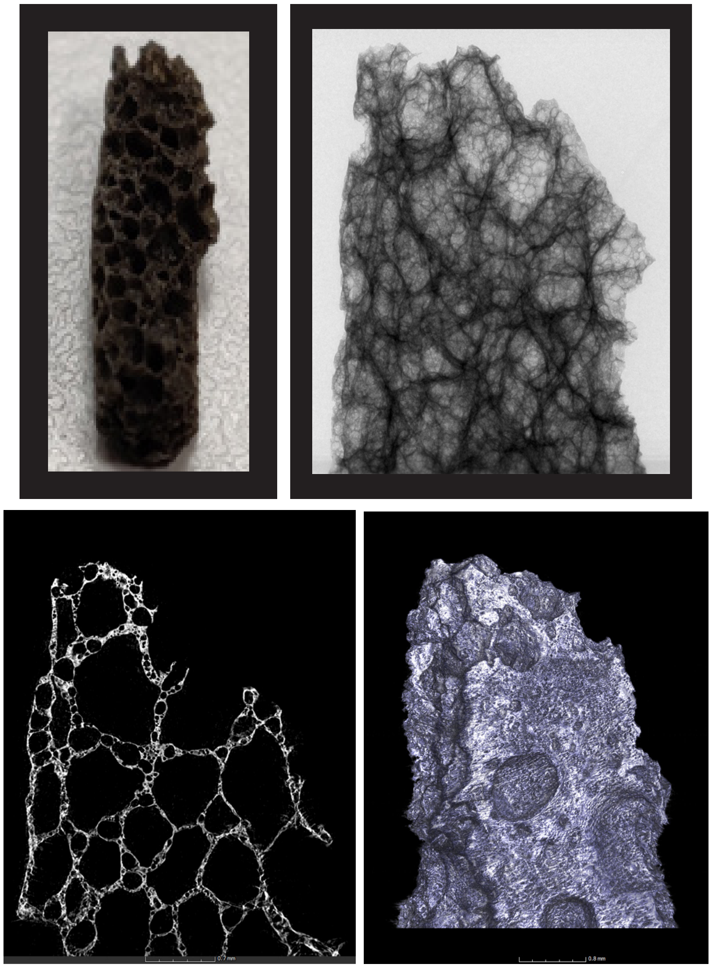
Sample: Kevlar composite (3D rendering)

Quality Assurance

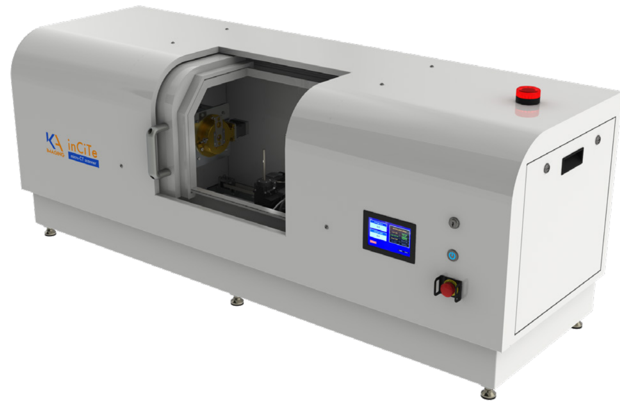
Sample: LED

MICRO-CT **APPLICATIONS** CONTINUED

Non-Destructive Testing (NDT)



Sample: Aggregate used in lightweight concrete (Top L: Photo, Top R: Projection, Bottom L: Example slices, Bottom R: 3D rendering)



In addition, the inCiTe™ 3D X-ray Microscope is designed with patented propagation-based, phase-contrast imaging to enhance detail of the fine structures that are typically X-ray transparent, without losses associated with grating-based phase contrast systems.

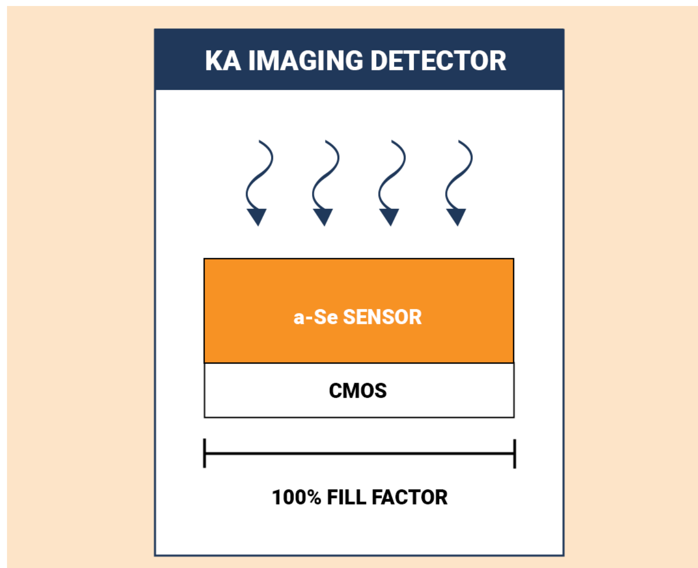


Figure 6: inCiTe™ 3D X-ray Microscope with direct conversion amorphous-selenium detection technology

KA IMAGING'S 3D X-RAY MICROSCOPE **WITH PHASE CONTRAST**

Combining some of the best features in micro-CT scanner design, the inCiTe™ benchtop 3D X-ray Microscope is the first commercial X-ray CT scanner that utilizes high spatial-resolution amorphous-selenium CMOS (a-Se) direct conversion detector technology exclusively developed by KA Imaging. The high conversion efficiency of the a-Se detector enables very high-speed sampling at low X-ray radiation doses. Owing to the high efficiency, unprecedented volumetric scan speed can be obtained at full resolution.

Moreover, the inCiTe™ 3D X-ray Microscope is equipped with a high-quality micro-focus X-ray source to achieve unparalleled resolution. Integrated software controls and simplified user interface enable a high degree of automation and reduce operator dependence. The size and weight of the inCiTe™ 3D X-ray Microscope are designed for minimum footprint, ease of transportation, and convenient integration into laboratory benchtop stations. The novel 3D X-ray Microscope features efficient, high-resolution X-ray imaging in a compact benchtop system. Table 1 shows features that are available only with the inCiTe™ 3D X-ray Microscope.

KA IMAGING'S MICRO-CT SCANNER **WITH PHASE CONTRAST** CONTINUED

Table 1: inCiTe™ features

UNIQUE FEATURES	DESCRIPTION	ADVANTAGES
Detection Efficiency	DQE = 40% at 10 cycles/mm	100% fill factor + direct conversion Up to 100x more efficient than scintillator type detectors
Micron-scale Pixel, Large Format	8 µm, 16 MP (4096 x 4096)	1. 4 µm true spatial resolution with maximum magnification 0.8 µm nominal resolution at maximum magnification (2 µm focal spot source)
Phase Contrast	Propagation-based	Bigger detector range (large energy range) vs. grating-based system
Spatial Resolution	MTF = 30% at 64 cycles/mm, 60kVp	Excellent small feature contrast imaging for polymers, and other low-density materials

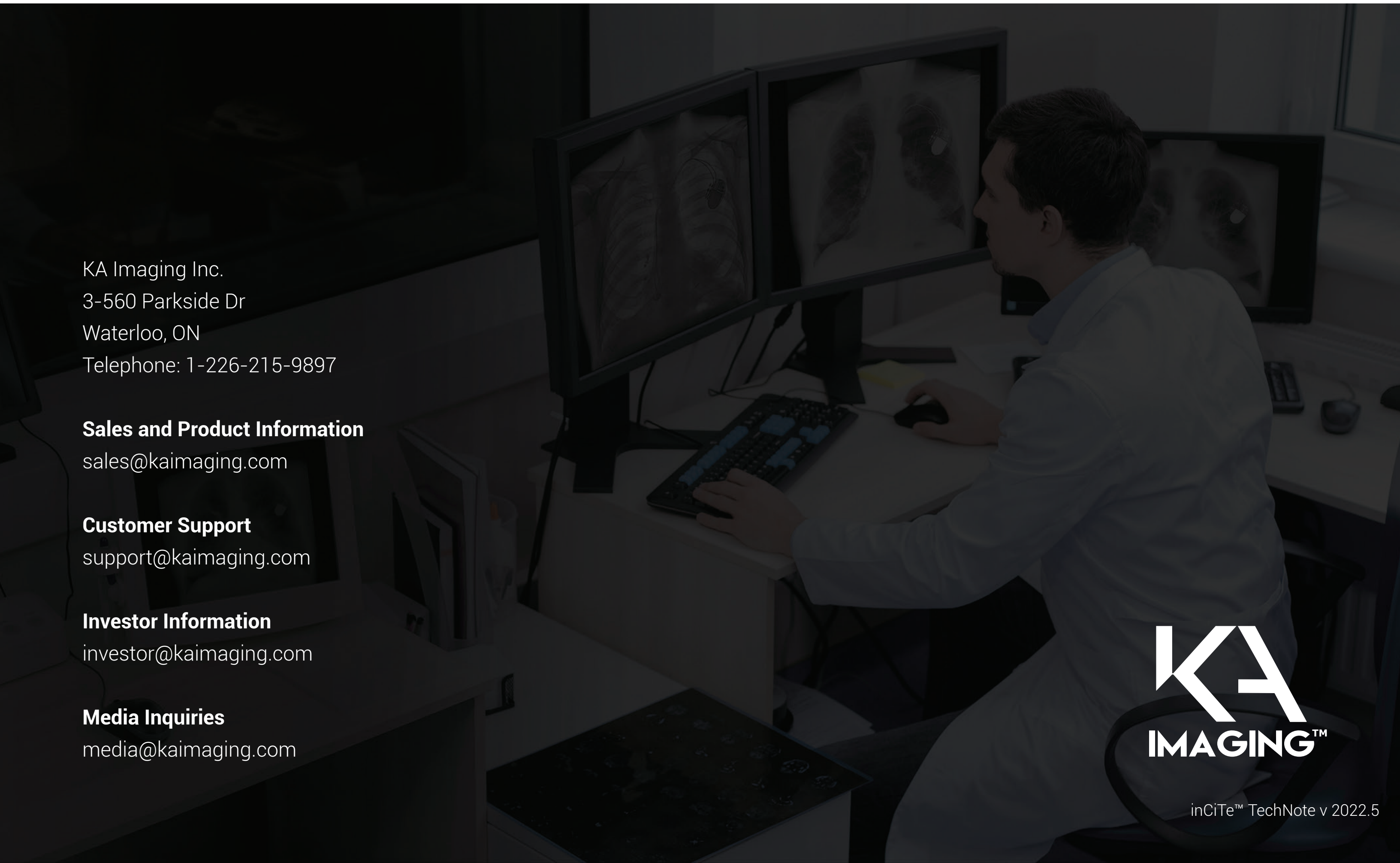
ABOUT **KA IMAGING**

Founded in 2015, KA Imaging is a spin-off from the STAR group at the University of Waterloo. Our company has successfully developed a line of X-ray imaging products based on a patented amorphous selenium process. The patented X-ray sensor technology provides the highest spatial-resolution direct-conversion X-ray detector in the world, with 100% fill factor and 30% MTF at 64 cycles/mm. Our main product offerings include benchtop 3D X-ray microscope, a high-resolution X-ray area detector for high-brilliance coherent X-ray applications, and a flat panel (FPD) for both medical and NDT applications.

REFERENCES

Scott, C. C.; (2019). PhD Thesis, University of Waterloo, Waterloo, Ontario, Canada.

Scott, C. C.; Parsafar, A.; El-Falou, A.; Levine, P. M; & Karim, K. S. (2015). IEEE International Electron Devices Meeting (IEDM), 30.6.1-30.6.4.



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