# Achieving true magnification in parallel ghost imaging at zero cost based on the cone beam characteristics of the X-ray tube

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## Abstract

Ghost imaging (GI), as a novel imaging technique, facilitates image acquisition under low-light conditions through single-pixel measurements, thus holding great potential in various application areas ranging from biomedical imaging, remote sensing imaging, biometrics, astronomy to 3D imaging. However, to reconstruct high-resolution images, GI typically requires a large number of single-pixel samplings, which is extremely time-consuming and poses practical limitations to its applications. Parallel ghost imaging treats each pixel of the position-sensitive detector as a bucket detector and simultaneously performs tens of thousands of ghost imaging operations in parallel. In previous work, we gradually achieved parallel ghost imaging with high pixel resolution, low dose, and ultra-large field of view. Parallel ghost imaging has demonstrated excellent performance and great potential. These developments demonstrate significant promise. However, since all our experiments were carried out at synchrotron radiation facilities under exceptionally favorable conditions—including nearly unlimited and continuous beamtime, monochromatic, pure, and energy-tunable X-rays, expensive and precise experimental equipment, and comprehensive supporting facilities—many researchers lacking such experimental conditions cannot replicate parallel ghost imaging. Meanwhile, the high cost also hinders its cross-disciplinary integration. Furthermore, we eliminated the synchrotron radiation source and completed the pipeline-style acquisition of parallel ghost imaging using rudimentary and inexpensive equipment in a manner easily replicated by other researchers. We achieved high-quality ghost imaging with an effective pixel size of 8.03 μm and an image size of 2880$×$2280 at a laboratory X-ray source. The total cost of transforming an X-ray computed tomography device into a parallel ghost imaging experimental platform is only $40. Parallel ghost imaging has been generalized from synchrotron radiation sources to X-ray tubes. However, a key problem remains unsolved. The object-arm signal on our laboratory light source was obtained through artificial fitting, and the true magnification relationship between the reference arm and the object arm has not been established. In synchrotron radiation experiments, we achieved true magnification using different magnifying optical lens groups. On the one hand, such lens assemblies are prohibitively expensive, making the generalization of parallel ghost imaging difficult once again. On the other hand, the flux of the X-ray tube is very low, leading to extremely poor efficiency. In this work, we demonstrate that, compared with the parallel beam of synchrotron radiation, the cone beam of the X-ray tube naturally enables true magnification when the detector is gradually moved away from the light outlet. We utilize only a single detector. When collecting the object-arm signal, the detector is positioned 30 cm from the light outlet, and when collecting the reference-arm signal, the detector is positioned 150 cm from the light outlet. These positions establish a 5×true magnification ratio, achieving super-resolution of parallel ghost imaging on the X-ray tube. A series of high-quality ghost imaging results with an effective pixel size of 7.095 µm and an image size of 2880×2280 were obtained through pipeline-style acquisition. The realization of true magnification based on the X-ray tube is a prerequisite for achieving ultra-large field-of-view and low-dose imaging. Implementing this approach without additional expenditure implies significant application value and commercial potential.

## Full Text

## Preamble

### Achieving True Magnification in Parallel Ghost Imaging at Zero Cost Based on the Cone Beam Characteristics of the X-ray Tube

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**Abstract:** Ghost imaging (GI), as a novel imaging technique, facilitates image acquisition under low-light conditions through single-pixel measurements, thus holding great potential in various application areas ranging from biomedical imaging and remote sensing to biometrics, astronomy, and 3D imaging. However, reconstructing high-resolution images typically requires a large number of single-pixel samplings, which is extremely time-consuming and poses practical limitations. Parallel ghost imaging treats each pixel of the position-sensitive

detector as a bucket detector and simultaneously performs tens of thousands of ghost imaging operations in parallel. In previous work, we gradually achieved parallel ghost imaging with high pixel resolution, low dose, and an ultra-large field of view, demonstrating excellent performance and great potential. While these achievements are exciting, all experiments were carried out at synchrotron radiation facilities with nearly luxurious conditions: virtually unlimited and continuous beam time, monochromatic and energy-tunable X-rays, expensive and precise equipment, and complete supporting facilities. Consequently, many peers lacking such experimental conditions cannot replicate parallel ghost imaging, and the high cost hinders its cross-disciplinary integration.

In this work, we eliminate dependence on synchrotron radiation and complete pipelined acquisition of parallel ghost imaging using rough, inexpensive equipment in a manner that is most easily replicated by others. We achieved high-quality ghost imaging with an effective pixel size of 8.03 µm and an image size of 2880$×$2280 using a laboratory X-ray source. The total cost of transforming an X-ray computed tomography device into a parallel ghost imaging experimental platform is only $40. Parallel ghost imaging has been generalized from synchrotron radiation sources to X ray tubes.

However, a key problem remains unsolved. The object arm signal on our laboratory light source was obtained through artificial fitting, and the true magnification relationship between the reference arm and the object arm has not been established. In synchrotron radiation, we achieved true magnification using different magnifying optical lens groups. On the one hand, such a set of lenses is very expensive, making the generalization of parallel ghost imaging difficult again. On the other hand, the flux of the X ray tube is very small, which leads to extremely low efficiency. In this work, we find that compared with the parallel beam of synchrotron radiation, the cone beam of the X ray tube naturally has the characteristic of true magnification by gradually moving the detector away from the light outlet. We only use one detector. When collecting the object arm signal, the detector is moved to a position 30 cm away from the light outlet, and when collecting the reference arm signal, the detector is moved to a position 150 cm away from the light outlet.

These two positions form a true magnification relationship of 5 times, achieving super resolution of parallel ghost imaging on the X ray tube. A series of high quality ghost imaging results with an effective pixel size of 7.095 µm and an image size of 2880×2280 in pipeline style acquisition were obtained. The realization of true magnification based on the X ray tube is a prerequisite for achieving ultra large field of view and low dose imaging. Completing this work at zero cost implies great application value and commercial potential.

## Introduction

The traditional imaging model primarily consists of three components: the light source, the ob- ject, and the optical system. In contrast, ghost imaging (GI), a novel imaging technique, employs a non-localized approach to separate detection from imaging. Ghost imaging involves splitting the light into two beams: one beam carries the object information but lacks resolution, while the other beam carries resolution but lacks object information. Neither beam alone is capable of imaging, but by correlating the two beams computationally, the object information can be reconstructed. Hence, ghost imaging is also referred to as correlation imaging.

Ghost imaging originates from the Hanbury-Brown and Twiss (HBT) experiment [1, 2]. In 1988, Klyshko [3] theoretically proposed a ghost imaging scheme using entangled photon pairs.

In 1994, Ribeiro et al. [4] discovered the phenomenon of ghost interference using entangled photon pairs. In 1995, Pittman et al. [5] experimentally demonstrated ghost imaging using en- tangled photon pairs. In 2002, Bennink et al. [6] realized ghost imaging with classical light sources, proving that entangled light sources are not a necessary condition for ghost imaging.

Furthermore, ghost imaging has been shown to be feasible in various fields, including atomic [7], electronic [8], neutron [9, 10], and X-ray [11–15] imaging. In 2008, Shapiro [16] theoretically proposed a computational ghost imaging scheme, making single-channel ghost imaging possible.

In 2009, Bromberg et al. [17] experimentally realized computational ghost imaging. In the same year, Katz et al. [18] integrated compressive sensing techniques from image processing with computational ghost imaging, significantly reducing the number of samples required for ghost imaging. This development made dose reduction in X-ray ghost imaging feasible. Moreover, ghost imaging has enormous potential across various application areas, including biomedical imaging [19], remote sensing [20], biometrics [21, 22], astronomy [23], and three-dimensional imaging [24, 25].

However, to reconstruct high-resolution images, Ghost imaging typically requires a large num- ber of single-pixel samples, which poses challenges for its practical application. The concept of parallel ghost imaging (PGI) was introduced by Kingston et al. [9] to address this issue. This method treats each pixel of a position-sensitive detector as an independent bucket detector, en- abling the simultaneous execution of tens of thousands of ghost imaging measurements at once.

Kingston et al. and Zhang et al. successfully demonstrated PGI in neutron [9] and X-ray [26,27], respectively. O. Sefi et al. customized a gold mask with extremely high aspect ratio structures through X-ray lithography technology, making high-energy X-ray parallel ghost imaging possi- ble. Moreover, they combined parallel ghost imaging with CT to achieve parallel ghost tomog- raphy [28].

In our previous work, we established a true magnification configuration between the reference arm and the object arm using lenses, achieving high-pixel-resolution parallel imaging at the sub-micron level (0.325 µm/pixel) and increasing the experimental efficiency from dozens of minutes to just a few minutes [29]. Zhao et al. achieved low-dose ghost imaging by using two detectors in crystal-splitting ghost imaging. By constructing an extra-large speckle space, we realized ghost imaging with an extra-large field of view of 14000×10000 pixels [30]. We also specifically proposed global ghost imaging for the bucket detector array architecture, which can achieve high-quality reconstruction with an ultra-low sampling rate of only 8 measurements.

Moreover, this method can eliminate the discontinuity between ghost imaging subsystems [31].

Subsequently, we replaced the crystal splitting with a computational ghost imaging framework to achieve low-dose ghost imaging, significantly improving the image quality and, for the first time, simultaneously realizing large-field-of-view, low-dose, and high-pixel-resolution ghost imaging [32].

However, the transformation of scientific research achievements has run into difficulties. All the above progress was completed relying on the Shanghai Synchrotron Radiation Facility. The nearly infinite and continuous light supply time, monochromatic, pure, and energy-adjustable X-rays, expensive and precise experimental equipment, and the complete supporting facilities -this series of almost luxurious services provided by synchrotron radiation make it impossible for many peers lacking experimental conditions to replicate parallel ghost imaging. At the same time, the high cost has also hindered its cross-disciplinary integration.

We got rid of the synchrotron radiation source and completed the pipeline-style collection of parallel ghost imaging with rough and inexpensive equipment in the most imitable way. Even- tually, with a laboratory X-ray source, we achieved ghost imaging with an effective pixel size of 8.03 µm, an image size of 2880×2280, and a minimum of 10 measurement numbers (a sampling rate of 0.62%) [33].

However, a key problem still remains unsolved. The object arm signal in our laboratory light source was obtained through artificial fitting, and the true magnification relationship between the reference arm and the object arm has not been established yet. In synchrotron radiation, we achieved true magnification using different magnification optical lens sets [29]. On one hand, such a set of lenses is very expensive, making the generalization of parallel ghost imaging difficult again. On the other hand, the flux of the X ray tube is very small, and adding an optical lens set in the light path will further reduce the flux, resulting in extremely low efficiency.

In this work, we find that compared with the parallel beam of synchrotron radiation, the cone beam of the X ray tube naturally has the characteristic of true magnification by gradually moving the detector away from the light outlet. When collecting the object arm data, the detector is moved to a position 30 cm away from the light outlet, and when collecting the reference arm data, the detector is moved to a position 150 cm away from the light outlet. These two positions form a true magnification relationship of 5 times. We used only one detector and achieved super resolution of parallel ghost imaging with the X ray tube without incurring any additional costs. A series of high quality ghost imaging results with an effective pixel size of 7.095 m and an image size of 2880×2280 were obtained through pipeline style acquisition. The realization of true magnification based on the X ray tube is a prerequisite for achieving ultra large field of view and low dose imaging. Completing this work at zero cost implies great application value and commercial potential, and will further accelerate the generalization of parallel ghost imaging in various fields. Parallel ghost imaging exhibits unique advantages with its non local imaging feature, such as low dose and low cost, and is expected to challenge traditional projection imaging.

## 2. Methods and experiments

Model For the ghost imaging model from a classical perspective, the bucket detector signals acquired from measurements in object arm can be written in the form of a matrix in Eq.1. 1 (1, 1) 2 (1, 1) (1, 1) 1 (1, 2) 2 (1, 2) (1, 2) ⋯⋯⋯ 1 ( , 1) 2 ( , 1) ( , 1) ⋯⋯⋯ 1 ( , ) 2 ( , ) ( , ) (1, 1) (1, 2) ( , ) The object' s transmittance function ( , ), which contains internal structural information of the sample, is the unknown target we aim to reconstruct in ghost imaging. Both the image size of the mask and the reconstructed ghost image of samples are × . The transmittance function of the k-th mask is denoted as ( , ), where = 1, ⋯, and = 1, ⋯, , respectively.

Fig. 1 [Figure 1: see original paper]. Experimental schematic diagram of true magnification parallel ghost imaging based on the cone beam characteristics of the X-ray tube. (b) Schematic diagram of the reference arm. (c) The speckle pattern collected in the reference arm, which contains no sample information but has high resolution. (d) Schematic diagram of the object arm. (e) The signal of the array bucket detector collected in the object arm, which contains sample information but has low resolution. When directly using traditional direct projection imaging, the imaging result is shown in (a). In contrast, if parallel ghost imaging is used, the imaging result is super-resolved and magnified as shown in represents the number of measurements, denotes the bucket detector signal during the - th measurement, and the sampling rate is defined as the number of measurements divided by the number of image pixels, i.e. × . A higher sampling rate leads to higher quality of ghost imaging. For the detector in the object arm, the incident X-ray photons need to pass through the mask and subsequently through the object, which means that the absorption of both the mask and object should be taken into account. Ghost imaging, at its essence, is solving underdetermined linear equation set. PGI simply utilizes this process repeatedly for all the single pixels of the bucket detector array in the object arm.

Algorithm PGI is based on the Total Variation Augmented Lagrangian Alternating Direction Algorithm [34] using compressive sensing. TVAL3 uses Total Variation Regularization (TV) as an iterative model: , . . = , is the speckle patterns, is the image of the object to be solved, is the measurements of the bucket detector, is the gradient of at pixel , . is the 1 norm. The Augmented Lagrangian method transforms a constrained model into an unconstrained objective function, and then uses the Alternating Direction method to solve the objective function at high speed.

## Experiment

In our previous work, we were able to modify any experimental platform capable of implementing computed tomography to achieve X-ray parallel ghost imaging. This only re- quires an extremely low cost of $40andisveryeasyforotherstoreplicate.Thelaboratorylightsourceusedisthemicrofocus X-raysource(XWT-225ThePlus)fromX-RAYWorX, featuringamaximumvoltageof225kV, minimumvoltag typeX-raytubewithadiamond-tungstentargetmaterial, aradiationangleof160^{\circ}, andsub-micronlevelresolution.ThedetectorisaCMOScamera(TeledyneDALSAShad-o-Box6KHS)with2940\times$2304 pixels, an effective area of 14.6 cm × 11.4 cm, and a resolution of 49.5 m.

## 2. Speckle Analysis

True magnification leads to improved resolution of the minimum effective characteristics of the speckles. Figure 2 [Figure 2: see original paper] presents the speckle pattern collected in the object arm, with the full width at half maximum (FWHM) of its point spread function (PSF) shown in the horizontal direction (b) and vertical direction (c). The speckle pattern collected in the reference arm is shown in (f), with its PSF FWHM in the horizontal and vertical directions displayed in (g) and (h), respectively. Comparison reveals that the resolution of the minimum effective characteristics has improved by more than twofold. The correlation degree between speckles is shown in (d) for the object arm and (i) for the reference arm, while the modulation ability of the mask is shown in (e) for the object arm and (j) for the reference arm.

The total cost of modifying the CT experimental platform is $40, which is precisely the price of the copper foam and sandpaper used to modulate the light field. From a commercial production perspective, experiments should minimize costs while achieving the highest possible image quality, a concept we continue to adhere to in this work. We achieve true magnification between the reference arm and object arm without incurring any additional costs. Precise mask movement is necessary for each measurement and is accomplished by placing the mask on the sample stage of the CT X-ray machine. True magnification requires the mask, sample, and object-arm detector to be positioned as close as possible to the light outlet. Consequently, the motor assembly carrying the mask should be as close as possible to the light outlet, while simultaneously positioning the object-arm detector as close as possible to the mask. Due to safety distance limitations, more than ten centimeters must be reserved between the mask and detector, with our sample stage placed within this gap. The distances from the mask, sample, and detector to the light outlet are utilized without waste, which is a necessary condition for achieving true-magnification parallel ghost imaging with an X-ray tube, as shown in Fig. 5(f). This involves a unique discussion of parallel ghost imaging under cone beam conditions. The magnification factor of true magnification and the effective size of the speckles are related to the distances from the mask, sample, object-arm detector, and reference-arm detector to the light outlet, which we elaborate on later.

The reference-arm detector is placed 150 cm from the light outlet, with the reference-arm optical path shown in Fig. 1(b). With the sample stage empty, the collected high-resolution speckle pattern is shown in Fig. 1(c). The object-arm detector is placed 30 cm from the light outlet, with its optical path shown in Fig. 1(d). The bucket detector array signal collected by the object-arm detector is shown in Fig. 1(e). Without the mask, traditional projection imaging achieved by the detector at 30 cm is shown in Fig. 1(a). Parallel ghost imaging non-locally correlates and calculates the object-arm signal (containing object information but low resolution) with the reference-arm signal (without object information but high resolution). It can reconstruct effects that traditional imaging achieves only at a 150 cm detection distance while operating at a 30 cm detection distance. The parallel ghost imaging reconstruction result is shown in Fig. 1(f), with the intuitive comparison between Fig. 1(e) and (f) proving that we have achieved super-resolution on the X-ray tube.

## 3. Super-Resolution Evidence

Whether super-resolution has truly been achieved requires substantial evidence. The mask is placed 4.7 cm from the light outlet, and the detector pixel size is 49.5  m. Due to cone beam magnification, the equivalent pixel sizes of the mask at the object arm (30 cm) and reference arm (150 cm) are 7.75  m and 1.55  m, respectively, as evidenced in Fig. 5(a) and (b). The effective pixel size of the reference arm is five times that of the object arm. This evidence is necessary but not sufficient, as the effective aperture size of the speckles may not increase proportionally with pixel resolution improvement, and this aperture size determines the theoretical upper limit of ghost imaging reconstruction resolution. Therefore, we present a series of discussions on the effective aperture size of speckles below.

In the experiment, the microfocus X-ray tube operates at 70 kV and 120 mA, implying that the output X-ray energy spectrum is continuous, including the tungsten characteristic peak with a maximum electron energy of 70 keV. The X-ray tube photon energy is much higher than synchrotron radiation, and photons with different energies pose difficulties for light field modulation. Discussions and analyses regarding the interaction between the mask and photons of different energies have been provided in our work on the generalization of parallel ghost imaging [33]. Therefore, we continue to adopt the mixed mask strategy consisting of four layers of 200-mesh sandpaper, a dense copper foam with 0.2 mm thickness and 10 m aperture, and three layers of 200-mesh sandpaper. With no sample placed, the speckle pattern collected by the object arm is shown in Fig. 2(a). The full width at half maximum (FWHM) of the point spread function (PSF) provides the minimum effective characteristic size of the object-arm speckle pattern: 39.7 m in the horizontal direction and 37.6 m in the vertical direction, as shown in Fig. 2(b) and (c). Similarly, the minimum effective characteristic size of the reference-arm speckle pattern is 16.3 m horizontally and 16.2 m vertically, as shown in Fig. 2(g) and (h). Comparison reveals that the minimum effective resolution provided by the reference arm is approximately 2.4 times that of the object arm, indicating that conditions for achieving super-resolution in ghost imaging are met. To avoid ineffective measurements in ghost imaging, we need random speckles to be as dissimilar as possible. The low correlation degree between speckle patterns demonstrates that random speckles can be approximately regarded as orthogonal to each other, as shown in Fig. 2(d) and (l). The modulation ability of the mask is shown in Fig. 2(e) and (j).

## 4. Results and True Amplification

From industrial and commercial perspectives, efficiently completing measurements of a series of samples is essential. Before parallel ghost imaging could be separated from synchrotron radiation, we had already achieved pipelined sample collection. For object-arm collection of a series of samples, only a single pre-recorded reference-arm dataset is necessary. The exposure time for measuring the reference arm is 8 seconds, while the exposure time for measuring the object arm is 0.1 seconds. We simulated factory pipeline collection using a set of chips (small, medium, and large). The actual photographs of the three chips are shown in Fig. 5(l), and their traditional direct projection images at 30 cm are shown in Fig. 5(i), (j), and (k).

Finally, we reconstructed a series of results with an image size of 2880×2280 and an equivalent pixel size of 7.095 m in a pipelined manner. Each pixel of the object-arm detector corresponds to a 5×5 pixel block of the reference arm, with results for different numbers of measurements/sampling rates displayed in Fig. 3. The traditional direct projection images of the chips at 150 cm are listed in Fig. 3 and 4(a), (l), and (w) as reference standards. After achieving true magnification, the experimental results demonstrate astonishing image quality while maintaining a large field of view and high pixel resolution. We confidently claim that such high-quality results are the first in the world in the field of X-ray ghost imaging. Structural similarity (SSIM) is an index that effectively measures the similarity between parallel ghost imaging results and the reference standard. The SSIM curve with measurement numbers ranging from 2 to 400 is shown in Fig. 5(g), providing strong evidence for our assertion.

We believe further exploration is necessary to verify the method’ s reliability. First, due to the CT platform’s radiation protection shell not being large enough, the reference-arm detector cannot be placed further from the light outlet, making a true magnification of 5×the current limit. Second, in our previous study on block size influence on reconstruction quality [26], we found that a 40×40 pixel block is optimal. Third, achieving true magnification between the reference and object arms requires precise registration, and a 5×5 pixel block is too small to distinguish alignment effects. Therefore, based on a true magnification of 5×, we further fit an artificially created 8×8 detector into a bucket detector to form a 40×40 magnification correspondence to explore imaging result reliability. A series of results with different measurement numbers/sampling rates for 40×40 pixel blocks are displayed in Fig. 4. Larger pixel blocks mean lower sampling rates, poorer image quality, and lower dose under the same number of measurements. Although image quality decreases, the successful reconstruction proves we have achieved registration between the reference and object arms at zero cost. The SSIM curve is shown in Fig. 5(h).

## 5. True Magnification

In our previous work, we achieved generalization of parallel ghost imaging for X-ray tubes. However, the object-arm bucket detector array was artificially fitted, and we failed to successfully establish a true magnification relationship between the object and reference arms. This meant that the super-resolution characteristic of ghost imaging was not realized, and thus the low-dose and large field-of-view advantages that rely on super-resolution could not be achieved either. In this work, we utilize the cone beam characteristics of the X-ray tube to achieve true magnification, solving the core problem of parallel ghost imaging with an X-ray tube. Some phenomena related to true magnification did not occur in previous work and require separate discussion.

The mask is 4.7 cm from the light outlet, the sample is 21.5 cm from the light outlet, the reference-arm detector is 150 cm from the light outlet, and the object-arm detector is 30 cm from the light outlet. Device diagrams of the reference arm are shown in Fig. 5(c), (d), and (e), and those of the object arm are shown in Fig. 5(f). In the object arm, the effective resolutions of the mask and sample are 7.75 m and 35.47 m, respectively, as shown in Fig. 5(b). In the reference arm, the effective resolutions of the mask and sample are 1.55 m and 7.095 m, respectively, as shown in Fig. 5(a). We found that the effective resolution of the speckle pattern is decoupled from the effective resolution of the sample, which differs significantly from parallel ghost imaging with synchrotron radiation and parallel ghost imaging with an X-ray tube without true magnification. The effective pixel size of the speckles in parallel ghost imaging is 1.55 m, while the effective pixel size of the sample is 7.095 m, as indicated in the scale bars of Fig. 2(f) and Fig. 3 or 4. In parallel ghost imaging with cone beam magnification, the magnification factors of the mask and sample are independent of their distances from the light outlet and are only related to the ratio of the distances of the detectors in the object and reference arms. A higher magnification factor requires the reference-arm detector to be as far from the light outlet as possible, though this is not as easily achieved as moving the object-arm detector closer to the light outlet. Moving the reference-arm detector several meters further away achieves the same magnification factor as moving the object-arm detector several centimeters closer, meaning the crowded optical path of the object arm is more cost-effective. The cone beam magnification also enlarges speckle size, which on one hand requires the mask to have smaller aperture characteristics, and on the other hand suggests that a structure with the sample in front and the mask behind may be more reasonable.

## 6. Conclusion

In conclusion, our previous work successfully achieved the three key characteristics of parallel ghost imaging—high pixel resolution, ultra-large field of view, and low dose—through synchrotron radiation. Additionally, we specifically proposed global ghost imaging for the bucket detector array architecture to eliminate discontinuities between blocks. The parallel ghost imaging framework has demonstrated immense application potential and commercial value. We accomplished the transformation from a CT X-ray machine to a parallel ghost imaging experimental platform at a minimum cost of only $40 via an approach that is most accessible for our peers to replicate. In this current work, the significant problem of the inability to achieve true magnification in parallel ghost imaging using an X-ray tube has been resolved at no cost, signifying that ghost imaging has taken another crucial step forward toward practical application and commercialization.

Although this work has addressed the core issue in parallel ghost imaging with an X-ray tube, it still falls far short of our expectations. A true magnification ratio of 40× is what we are striving for. Parallel ghost imaging must reconstruct sample details that traditional imaging methods cannot capture, with the disparity large enough to be discernible with the naked eye. In other words, achieving a sample effective resolution significantly higher than the current level is a rigid criterion for parallel ghost imaging to replace traditional imaging. This core challenge is the only obstacle hindering parallel ghost imaging from achieving industrialization. If it can be overcome, parallel ghost imaging will have a profound impact on the field of medical imaging.

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**Data Availability Statement.** Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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