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# Literature Review of Fabricated Artifacts for X-ray Computed Tomography

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## Abstract

This report provides a comprehensive literature review of fabricated artifacts, commonly referred to as phantoms, used for the performance evaluation of X-ray computed tomography (XCT) systems. As XCT is increasingly adopted for high-precision metrology in the industrial sectors, including semiconductor manufacturing, establishing confidence in measurement results through well-characterized references is essential. This review categorizes available artifacts into two primary groups: those developed for spatial resolution assessment—such as line-pair gratings and Siemens stars—and those designed for defect detection studies. We reviewed the designs of commercial phantoms alongside recent research-driven developments at the National Institute of Standards and Technology (NIST). Special emphasis is placed on advanced microfabrication techniques, including focused ion beam (FIB) milling, laser micromachining, and deep reactive ion etching (DRIE), which enables the creation of controlled internal flaws with sub-micrometer precision. The report identifies critical challenges in the field, such as the complexities of non-destructive characterization, and the need for artifacts that better represent complex 3D geometries and multi-material composition. We conclude with recommendations for future phantom development, highlighting the necessity of standardized metrology to ensure reproducibility and compatibility across diverse XCT platforms.

## Keywords

Defect detection; Fabricated artifacts; Metrology; Microfabrication; Nondestructive evaluation; Phantoms; Probability of detection (POD); Semiconductor packaging; Spatial resolution; X-ray computed tomography (XCT).

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## Acknowledgments

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## Author Contributions

**John A. Wu**: Writing- Original draft preparation. **Felix H. Kim**: Writing- Reviewing and Editing, Supervision.

## 1. Nomenclature & Terminology

This section defines the terminology used in this article. X-ray computed tomography (XCT) is a non-destructive, three-dimensional (3D) imaging technique that utilizes multiple X-ray projections and computer algorithms to create detailed volumetric images of an object's external and internal structure. Depending on the sample materials, size, and required spatial resolution, different XCT instruments can be used (e.g., nano-CT (CT scans performed at nanometer scale), micro-CT (CT scans performed on a micrometer scale), industrial CT (maximum source accelerating voltage from 225 kV to 450 kV), and high-energy CT (e.g., X-ray energy at MeV)). There are overlaps among the different instrument categories in terms of achievable spatial resolution. In this paper, we focus on phantoms typically used for nano-CT and micro-CT instruments, but they can be extended to some industrial CT instruments.

The phrase "artifact" is commonly used in XCT applications in two different contexts: 1) Imaging Artifacts: undesired distortions in imaging during data acquisition or reconstruction, and 2) Fabricated Artifacts: artificially fabricated structures used to test and evaluate XCT system performances. To avoid confusion, each term will be clearly stated, defined, and used throughout this report.

### 1.1. Imaging Artifacts

Imaging artifacts are distortions or non-physical features that appear in reconstructed XCT datasets due to issues, such as X-ray physics and interaction with materials, acquisition settings, reconstruction algorithms, or sample shift/motion during the scan. Some examples are shown in **Fig. 1** and include:

- Beam Hardening: Occurs because X-ray sources produce a polychromatic spectrum. As the beam passes through a sample, lower-energy photons are absorbed more readily, increasing the "mean energy" of the remaining beam. This results in cupping artifacts, where the center of a uniform object appears less dense than the edges, or streaking between high-density materials [1].

- Photon Starvation: This occurs when the detector receives an insufficient signal because the X-ray beam is almost entirely attenuated by highly dense parts of the sample. It typically manifests as severe, noisy metal artifacts and dark streaks emanating from dense components, such as steel screws or implants.
- Scattering: Caused by X-ray photons being deflected (primarily via Compton scattering) rather than absorbed. The effect distorts the image signal at the detector and becomes more pronounced at higher energies as the relative contribution of Compton scattering increases [2].
- Ring artifacts: Concentric rings appearing in the reconstruction, usually resulting from detector non-uniformity or individual pixel malfunctions. [3]
- Motion artifacts: Blurring or misalignment caused by the sample shifting or vibrating during the data acquisition process.

While this review focuses on industrial and semiconductor applications, it is important to note that other domains have established rigorous standards for artifact characterization. For instance, in the security screening and homeland security sectors, the IEEE/ANSI N42.45 standard [4] provides specific test methods for evaluating the image quality of XCT systems. This standard describes procedures to quantify beam hardening and streak artifacts for reliable analysis.

Throughout this report, the term “Imaging Artifacts” will refer to these features and phenomena.

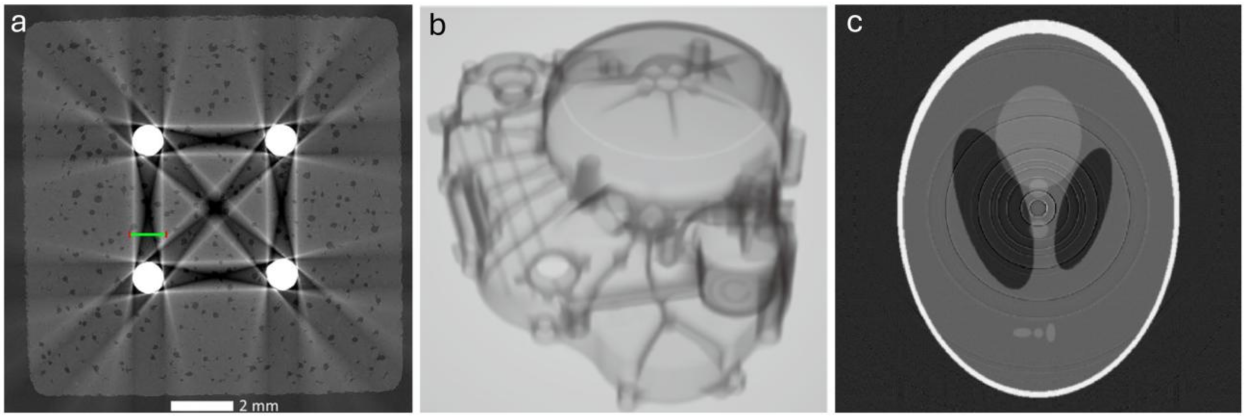

**Fig. 1. Common imaging artifacts from scanning procedures or reconstruction processes. a) streaking, b) scattering, c) ring artifacts. [1-3].**

## 1.2. Fabricated Artifacts (Phantoms / Test Objects)

Fabricated artifacts, also known as phantoms or test objects, are physically manufactured or engineered with features designed to test, calibrate, or evaluate various aspects of XCT system performance. Some examples include:

- Features to estimate spatial resolution: common features are bar patterns and Siemens stars[1] [5–9].
- Geometrical features to determine dimensional measurement accuracy or calibration: features such as spheres, rods, and fiducials [10–12].
- Controlled engineered flaws to assess detection capability: manufactured features such as voids, cracks, holes, or vias [13].

Beyond resolution and geometric calibration, it’s worth noting that another class of phantoms exist to evaluate materials discrimination capabilities. This is particularly relevant in security and medical XCT, where dual energy beams are used to characterize effective atomic number. Those phantoms utilize low-contrast material steps, often based on differences in physical density or atomic number, to verify a system’s ability to distinguish between distinct substances such as chemicals and bone or soft tissue [14]. While currently more common in security and medical imaging, materials discrimination phantoms represent an emerging area for industrial XCT.

Those mentioned features are produced intentionally and do not arise from the sample or imaging process. Throughout this report, the term “Fabricated Artifacts” or “Phantoms” will refer to manufactured structures designed for XCT performance assessment.

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[1] Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

## 2. Introduction

X-ray computed tomography (XCT) has become a crucial tool for non-destructive material characterization and defect detection. As XCT technologies are adopted across industries and continue to advance, the need for quantitative performance evaluation has increased correspondingly. To ensure high confidence in XCT measurement results, it is essential to characterize the original properties of the scanned sample and account for imaging defects introduced during acquisition and reconstruction. By utilizing a sample with features of precisely known dimensions and properties, researchers can introduce a controlled standard to isolate system-based errors from material features.

Fabricated artifacts – also referred to throughout the report as *phantoms* – are intentionally introduced to evaluate the system performance. As defined by NIST, phantoms serve as proxies for the objects being imaged, providing a well-characterized medium to evaluate how an imaging system captures data [15]. These artifacts are engineered structures with features of known geometry, material composition, and spatial arrangement, designed to provide ground-truth references for evaluating system performance. Their designs enable quantitative assessment of resolution, contrast, detectability, geometric accuracy, and reconstruction reliability. As XCT becomes more widely used in industrial inspection (e.g., defect detection) and failure analysis (e.g., in semiconductor manufacturing), the role of well-characterized phantoms is becoming increasingly central to establishing measurement standards.

Standardized phantoms are engineered with controlled features, such as resolution gratings, bar patterns, hole arrays, spherical designs, and multi-material interfaces achieved through procedures such as lithography, etching, laser machining, or other microfabrication technologies. Such features create and enable the evaluation of spatial resolution, contrast, probability of detection (POD), and geometric confidence for two-dimensional radiographic measurements. With the widespread use and rising importance of XCT analysis, phantoms have become more available commercially, such as those produced by Quality Assurance in Radiology and Medicine (QRM)[2], Japan Inspection Instruments Manufacturers Association (JIMA)[3], and Nippon Telegraph and Telephone Advanced Technology (NTT-AT)[4]. Recent work at NIST and other institutions have also demonstrated the potential of lithographically defined features for XCT evaluation.

This review provides a comprehensive survey and organization of currently available XCT artifacts or phantoms. There will be an emphasis on the design and fabrication of phantoms or flaw-controlled artifacts, alongside quantitative metrics and applications for available XCT artifacts or phantoms. This report reviews commercial products, industrial practices, peer-reviewed literature, and recent advances in microfabricated technology, including NIST-developed phantoms. Due to copyright issues, pictures or designs of the commercial phantoms are not shown in the report, but readers are encouraged to refer to the manufacturer's websites. The phantoms/artifacts developed for dimensional measurements (e.g., those based on well-characterized balls or spheres) were outside the scope of the report[16].

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[2] https://www.qrm.de/en/micro-ct-bar-pattern-phantoms
[3] https://www.jima.jp/english/assen-e.html
[4] https://keytech.ntt-at.com/en/xray/prd_0024.html

## 3. Artifacts Developed for Resolution Assessment

To evaluate the imaging performance and limits of an XCT system, researchers and inspectors utilize artifacts specifically designed to quantify resolution and geometric sharpness. These phantoms commonly consist of a wide range of geometric features, such as bar patterns and the Siemens star design. Such designs provide a direct means of assessing the instrument's spatial resolution capabilities by presenting periodic patterns that test the system’s ability to distinguish closely spaced features. These features are often used for 2D radiography-based spatial resolution assessment, but some 3D CT applications are also being developed.

### 3.1 Phantoms for 2D Resolution Assessment

This category of artifacts consists of planar, high-contrast targets designed to evaluate the in-plane spatial resolution of XCT systems. These phantoms typically feature high-attenuation materials like gold, tungsten, or tantalum deposited onto low-density substrates. Because these structures are manufactured using thin-film lithography or micro-electroplating, they offer exceptionally sharp edges and features down to the nanometer scale. They are particularly effective for determining the Modulation Transfer Function (MTF) and the visual resolution limits of micro-CT and nano-CT systems by providing a clear, two-dimensional ground truth.

JIMA of Japan produces a series of radiographic and CT resolution test charts that serve as artifacts for assessing baseline image quality in industrial XCT systems [17]. These targets are designed for 2D radiography-based resolution assessment. There is only one product commercially available as of the writing of this report, the RT RC-05B, but information on the other previous X-ray resolution charts is still accessible on the JIMA official website. The RT RC-02B, 04, and 05B are all similarly designed, with bars consisting of high-contrast materials for X-rays. The 02B and 04 models have Tungsten bars filled into $SiO_2$ substrates, while the 05B has Au-filled $SiO_2$. Feature widths typically range from approximately 0.1 µm to several tens of micrometers.

Microworks GmbH (Germany) develops precision microstructures and resolution targets for X-ray imaging quality control and nondestructive testing, with products that include standardized resolution targets tailored for X-ray imaging calibration [18]. These targets are designed for 2D radiography-based resolution assessment. Microworks resolution targets are typically fabricated on approximately 200 µm-thick silicon substrates, incorporating gold absorber patterns with nominal bar patterns with feature sizes from 0.3 µm up to 5 µm in their standard “Yxlon” targets, and features as small as 3 µm in specialized “NanoXSpot” four-quadrant targets. Microworks manufactures these artifacts using advanced lithographic technologies, including electron-beam lithography, direct-write UV laser lithography, deep X-ray lithography (LIGA), and two-photon grayscale lithography—followed by electroplating in gold and nickel alloys to define high-aspect-ratio microstructures with precise dimensional control.

NTT-AT of Japan produces a series of high-precision X-ray resolution charts (XRSO series) that are widely used for evaluating the spatial resolution and contrast performance of synchrotron radiation systems [19]. These targets are designed for 2D radiography-based resolution assessment. Those artifacts have patterns fabricated on a thin silicon-nitride membrane substrate, onto which high-attenuation metallic absorber patterns (tantalum in this case) are deposited to form line, bar, and grid structures. The thin film provides sharp absorber edges, producing well-defined boundaries to aid in signal detection. There are three designs in the XRSO series, XRESO-100, XRESO-50HC, and XRESO-20. The designs all feature line bars and a Siemens star. As listed in the public information, XRESO-100 has feature sizes from 100 nm to 800 nm, XRESO-50HC has patterns with a minimum feature size of 50 nm, and XRESO-20 has features down to 20 nm.

### 3.2 Phantoms for 3D Resolution Assessment

Unlike planar targets, 3D resolution phantoms are engineered to evaluate the volumetric performance of XCT systems across all spatial axes. Providers offer artifacts that incorporate three-dimensional features—such as spheres, 3D nanostructures, or chips suspended in resin—to assess how a system handles complex geometries. These phantoms are essential for identifying artifacts that may not be visible in 2D, such as axial blurring or geometric non-linearities caused by the 3D reconstruction algorithm. By using 3D structures, researchers can confirm spatial resolution is consistent throughout the entire scanned volume, rather than just within a single optimized plane.

QRM of Germany offers a selection of high-precision XCT bar-pattern and line-pair phantoms, intentionally designed to aid X-ray evaluation in the medical field [20]. These reference artifacts are used to evaluate spatial resolution in micro-CT and conical-beam CT, rather than radiography. The phantoms consist of silicon or resin substrates with trenches and dots patterned into them. The available micro-CT bar pattern phantoms are available in two size ranges: standard and Nano. The standard phantom offers options of the etched chips either mounted in air or encapsulated in resin, with line widths and dots ranging from 5 µm to 150 µm. The Nano version has line widths and dots from 1 µm to 10 µm.

XRnanotech (Switzerland) develops ultra-high-resolution X-ray targets for nanoscale and sub-micrometer imaging applications, including nano-CT and X-ray microscopy operating at the limits of spatial resolution [21]. Their products consist of 3D structured test artifacts fabricated on silicon-based substrates and designed to provide high-contrast features. Publicly available specifications describe test structures such as line arrays and Siemens stars, with lateral feature sizes ranging from 10 nm to 10 µm. XRnanotech advertises as a provider of highly customizable samples, utilizing etching techniques such as lithography and direct material removal, or construction via direct laser writing (DLW) or two-photon polymerization (2PP). Together, these fabrication capabilities allow XRnanotech to create nanostructured targets with feature dimensions well below one micrometer, suitable for high-resolution XCT and X-ray microscopy calibration.

## 4. Phantoms Engineered for Defect Detection

While standard resolution targets are effective for qualifying a system’s peak spatial frequency, evaluating a system's ability to identify specific material flaws requires artifacts designed for defect detection. Unlike periodic gratings, these phantoms utilize controlled 'flaws'—such as voids, inclusions, or high-aspect-ratio channels—to establish a probability of detection (POD) baseline. By embedding features of known geometry within realistic material matrices, these artifacts bridge the gap between idealized resolution and practical measurement confidence. This section focuses on recent developments in flaw-controlled phantoms. These types of phantoms are inherently used for 3D XCT measurements. By comparing a reconstructed dataset from a scanned phantom to its known physical dimensions, operators can identify scenarios in which system noise or blurring prevents clear feature separation. This comparison directs the operator to optimize scanning parameters or establish the instrument’s precise measurement limits.

Aletheia Imaging Solutions (United Kingdom) is a metrology-oriented company spun out from the University of Manchester that designs and manufactures advanced three-dimensional spatial calibration targets and associated analysis software specifically for XCT [22]. Their image quality indicators (IQIs) and representative quality indicators (RQIs) consist of feature clusters with dimensions down to approximately 1 µm. IQIs are artifacts used to quantify the general performance of an imaging system, such as its sensitivity and resolution under specific scanning conditions, whereas RQIs are application-specific targets that mimic the geometry and material composition of a particular part for more accurate assessment. Core elements typically include high-density materials, mentioned on their website, such as metals, ceramics, glass, and plastics as absorbers, which produce high contrast in XCT data due to their large mass attenuation coefficients. Aletheia’s 3D calibration targets are fabricated using manufacturing processes not publicly disclosed, but the company emphasizes the use of “most advanced manufacturing routines” to achieve features as small as ≅ 1 µm and collaborates with the National Physical Laboratory (NPL) to provide independent dimensional characterization and traceability of its targets.

Recent studies at NIST have provided a systematic investigation into the fabrication of phantoms for XCT, with the objective of achieving quantitative POD assessment, algorithm validation, and simulation-to-experiment comparison. In a recent report [13], Kim et al. evaluated multiple fabrication methods—including focused ion beam (FIB) milling, laser micromachining, and stepper photolithography combined with deep reactive-ion etching (DRIE)—to understand the achievable feature sizes, geometric fidelity, throughput, and suitability of each technique for producing controlled artifacts relevant to XCT performance studies. FIB milling was used to fabricate cylindrical holes in stainless steel substrates with diameters and depths up to approximately 40 µm, demonstrating dimensional control at small length scales, despite relatively low fabrication throughput and limited scalability. Laser micromachining enabled faster production of holes with diameters ranging from roughly 25 µm to 200 µm, making it suitable for larger-scale defect fabrication; however, tapering of sidewalls and increased surface roughness were observed for smaller features, introducing geometric variability that can complicate XCT datasets.

By contrast, stepper photolithography followed by DRIE processing was the most efficient and optimal method for generating high-density, repeatable microscale feature arrays. Based on these procedures, cylindrical holes with diameters ranging from 4.4 µm to 400 µm were created on a silicon wafer. These techniques are known to be applicable to sub-micrometer features. The advantage of lithography here lies in its ability to precisely define feature diameters and locations. DRIE, on the other hand, offered near-vertical sidewalls with high aspect ratios that are optimal for volumetric XCT analysis. To achieve three-dimensional internal defects with precisely known geometry and position, silicon wafer bonding was used as an encapsulation technique for the created cavities. The method of encapsulating these defects within tightly bound wafer bonds is a major consideration in XCT analysis because it precludes surface-access artifacts and instead enables detection within a more realistic representation.

NIST is currently expanding the research activity to fabricate artifacts with engineered defects to support the inspection of advanced semiconductor packages through the NIST CHIPS metrology R&D program[13].

## 5. Challenges, Open Issues & Future Directions.

Although considerable advances have been made in the fabrication of manufactured artifacts and phantoms for XCT performance evaluation, some technical difficulties remain. These include limitations imposed by fabrication and characterization techniques, material selection, and the complexity of modern imaging procedures.

Limitations in micro- and nanoscale fabrication pose a significant challenge. As feature sizes fall below a few micrometers, process complexity, surface roughness, and unintended geometry introduce considerable challenges. Although advanced methods such as lithography and nanofabrication are available, defects can still be introduced into the fabricated artifact itself, including sidewall tapering, micro-roughness, corner rounding, and bonding voids. These features often introduce ambiguity when interpreting the XCT measurement results.

There are challenges associated with characterizing fabricated features in terms of size and uncertainty. Scanning electron microscopy (SEM) offers higher accuracy than XCT measurements and is a suitable tool for characterization. SEM can only measure the surface, and destructive characterization may be needed to measure the depth of the feature. This approach works well for simple geometric features when the manufacturing process is highly repeatable, such as lithography and etching. Non-contact optical profilometers (e.g., laser-scanning microscopy and white-light interferometry) may work, depending on the depth and hole sizes. Accuracy generally decreases for sub-micrometer holes with high aspect ratios for this type of technique.

The choice of material is an important consideration. For radiographic applications, highly attenuating materials such as tungsten or gold may be acceptable for assessing spatial resolution. For determining defect-detection capability in CT applications, it is important to use materials with attenuation properties similar to those of the actual samples. Many advanced semiconductor packaging features involve less attenuating Cu, for example. More research is needed to identify suitable manufacturing techniques for these materials.

Material stability also poses an additional challenge, particularly for long-term use of phantoms in calibration and benchmarking. Common artifact materials include metals, polymers, ceramics, and silicon, each with distinct properties. Because an artifact may be exposed to thermal cycles, humidity, radiation doses, and physical handling over an extended period, it may undergo dimensional drift. Multi-component artifacts are especially susceptible, as thermal drift or aging effects can cause geometric changes among the differing materials.

Several available phantoms, such as line-pair or Siemens star phantoms, have been developed to assess spatial resolution for visual discernment. This is an indirect measure of detection capability, as visual detection is sensitive to contrast and noise. These phantoms are often designed for two-dimensional measurements and do not account for effects that occur during CT scanning, reconstruction, or automated defect-detection algorithms. More research is needed to develop engineered-defect artifacts for XCT applications. Furthermore, X-ray computed laminography (XCL) is gaining interest for high-throughput inspection of semiconductor chips or wafers. It is desirable to develop artifacts suitable for such relevant measurement strategies.

Table 1 summarizes the commercially available artifacts' materials, applications, and features sizes. Commercially available phantoms or fabricated artifacts span a broad range of feature sizes, materials, and intended applications, reflecting the diversity of XCT system capabilities and measurement objectives.

**Table 1. Compilation of commercially available artifacts and their feature details.**

| Manufacturer/Product | Phantom Material | Contrasting material | 2D/3D | Feature sizes | Resolution (line pair/mm) |
|---|---|---|---|---|---|
| QRM Micro CT Air[5] | air / plastic | silicon / air | 3D | 5 – 150 um | 100 – 3.3 |
| QRM Micro CT Resin[5] | resin | silicon / resin | | | |
| QRM NANO[5] | air / plastic | silicon / air | 3D | 1 – 10 um | 500 – 50 |
| JIMA RT RC-02B[6] | Si base | Tungsten / $SiO_2$ | 2D | 0.4 – 15 um | 1250 – 33.3 |
| JIMA RT RC-04[6] | Si base | Tungsten / $SiO_2$ | 2D | 0.1 – 10 um | 5000 – 50 |
| JIMA RT RC-05B[6] | Si base | Au / $SiO_2$ | 2D | 3 – 50 um | 166.6 – 10 |
| NTT-AT XRESO-100[7] | Si base | Ta / air | 2D | 100 – 800 nm | 5000 - 625 |
| NTT-AT XRESO-50HC[7] | Si base | Ta / air | 2D | 50 nm | 10,000 |
| NTT-AT XRESO-20[7] | Si base | Ta / air | 2D | 20 nm (radial) | 25,000 |
| XRnanotech Micro CT[8] | $Si_3N_4$ | Au, Ir | 2D | 10 nm | 50,000 |
| XRnanotech Resolution target[9] | Si | Au, $SiO_2$ | 2D | 0.01 – 12 um | 50,000 – 41.66 |
| XRnanotech 3D Nanostructures | | Polymer, Metal / Air | 3D | nm - mm | |
| Microworks Yxlon[10] | Si | Au / Si | 2D | 0.3 – 5.0 um | 1666.66 - 1000 |
| Microworks NanoxSpot[10] | Si | Au / Si | 2D | 3 – 12 um | 166.66 – 41.66 |
| Aletheia[11] | Various metallic materials such as Al, Ni, Ti, W etc. [19] | air | 3D | ≤ 1 um | |

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[5] https://www.qrm.de/en/micro-ct-bar-pattern-phantoms
[6] https://www.jima.jp/english/assen-e.html
[7] https://keytech.ntt-at.com/en/xray/prd_0024.html
[8] https://www.xrnanotech.com/products/micro-ct-test-targets/
[9] https://www.xrnanotech.com/products/resolution-targets/
[10] https://www.microworks.de/product/resolution-target
[11] https://aletheia-solutions.com/targets/

## 6. Conclusion

This review examines fabricated artifacts in the context of XCT, highlighting their complementary roles in assessing the system performance. Fabricated artifacts and phantoms provide a critical means of assessing system performance (spatial resolution or defect detection capability) by offering controlled, repeatable reference structures.

A survey of existing phantoms reveals a diverse range of designs, ranging from commercial resolution charts to advanced micro- and nano-fabricated artifacts developed for high-resolution and application-specific studies. Each class of phantom addresses a distinct category of metrics, and no single design currently satisfies all requirements for resolution assessment. Recent NIST-led studies demonstrate how fabrication techniques and 3D encapsulation strategies can produce phantoms with known ground-truth geometries, enabling rigorous POD studies and validation of simulation and reconstruction methods. There is still a lack of artifacts available to directly assess the defect detection capability.

Based on this review, several recommendations emerge for the design and use of future XCT phantoms. First, phantom designs should align with their intended measurement objectives, such as system qualification, defect detection, or algorithm validation. Second, fabrication methods should prioritize reproducibility and compatibility with intended metrology methods. Finally, comparisons between well-characterized physical phantoms and corresponding XCT simulations can help clarify system behavior and associated uncertainties.

All commercial phantoms were manufactured outside the United States. NIST recognizes the gap in this research area, which falls within its mission to advance measurement science to support the U.S. manufacturing industry. XCT phantoms in the upcoming developments are likely to use increasingly complex three-dimensional geometries, multi-materials for realistic contrast and imaging artifacts, and micro-scale features that better reflect detection challenges. Advances in microfabrication and materials characterization will enable more application-target artifacts, while standardized metrology methodologies will remain essential for ensuring consistency and comparability. Together, these developments will spearhead the continued maturation of XCT as a quantitative, reliable tool for metrology and nondestructive evaluation.

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