Feasibility of Perioperative Micro–Computed Tomography of Human Lung Cancer Specimens

A Pilot Study

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• Context.—Lesion localization during intraoperative frozen section of lung resection specimens can be challenging. Imaging could aid lesion localization while enabling 3-dimensional specimen analysis.

Objective.—To assess the feasibility of integrating micro–computed tomography (micro-CT) into the perioperative evaluation of fresh surgical lung resection specimens.

Design.—Fresh lung specimens from patients with a presumptive diagnosis of lung cancer were imaged with micro-CT prior to routine histopathologic and molecular analysis. Micro-CT images were assessed to determine image quality, lesion size, and distance from lesion to the nearest surgical margin. Micro-CT measurements were compared to pathologic measurements using Bland-Altman analysis.

Results.—A total of 22 specimens from 21 patients were analyzed (mean image acquisition time, 13 ± 6 minutes).

Histologic quality of imaged specimens was indistinguishable from a control group of nonimaged lung specimens. Artifacts, most commonly from specimen deflation (n = 8), obscured fine detail on micro-CT images of 10 specimens. Micro-CT could successfully localize the target lesion in the other 12 specimens. Distance to the nearest surgical margin was determined in 10 specimens. Agreement of micro-CT with final pathology was good, with a mean difference of −2.8% (limits of agreement −14.5% to 20.0%) for lesion size and −0.5 mm (limits of agreement −4.4 to 3.4 mm) for distance to nearest surgical margin.

Conclusions.—Micro-CT of fresh surgical lung specimens is feasible and has the potential to evaluate the size and location of lesions within resection specimens, as well as distance to the nearest surgical margin, all without compromising specimen integrity.

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Although lung cancer remains the leading cause of cancer-related mortality,1 lesions detected at an early stage, prior to nodal or distant spread, are amenable to curative resection. Fundamental to determining the appropriate surgical procedure is the ability to rapidly and reliably establish a histopathologic diagnosis, evaluate for the presence of invasion, and assess lesion distance to surgical margins, all at the time of surgery. This information is currently determined with intraoperative frozen sections, in which a small fraction of the surgical specimen is frozen, stained, and assessed microscopically to answer whether a completion lobectomy should be performed instead of a wedge resection.2 This preliminary intraoperative evaluation is followed by detailed histopathologic analysis of the entire specimen, often with molecular analysis, with results reported several days to a week after the resection. In the intraoperative setting, localization of the target lesion within lung resection specimens can be challenging, particularly for small and subsolid lesions, and final pathologic analysis may require the expenditure of considerable labor and resources to scrupulously section the entire specimen.3,4 With the movement toward tissue-conserving surgery, such as wedge resection, assessment of surgical margins and invasive tumor components is becoming increasingly important for intraoperative decision-making.5,6 Therefore, tools that permit rapid 3-dimensional (3D) analysis of the whole resection specimen to provide macroscopic tissue context could guide localization of the target lesion, thus expediting intraoperative pathologic assessment and diagnosis.7

Micro–computed tomography (micro-CT) could help meet this clinical need by allowing lesion visualization and
assessment within fresh surgical specimens. Although the principles of micro-CT are analogous to those of conventional CT, the technology is capable of much finer resolution (below 100 microns). Although historically used as a research tool for small animal imaging and material analysis, micro-CT has recently emerged as a method for imaging explanted human tissues. For example, micro-CT analysis of fixed explanted lungs has provided insights into diffuse lung disease. Application of micro-CT to fresh human tissue, however, has thus far been limited to breast lumpectomy specimens.

Intraoperative 3D specimen assessment by micro-CT has the potential to make a significant clinical impact in lung cancer care. However, whether micro-CT can be employed safely in this setting, without imparting damage to lung specimens via irradiation or significantly delaying specimen processing prior to routine pathologic and molecular analysis, has not been previously studied. Therefore, the purpose of this study was to assess the feasibility of using micro-CT to evaluate fresh surgical resection specimens, an essential preliminary step in determining the role of micro-CT in intraoperative assessment. We hypothesized that micro-CT could be integrated into the existing workflow without compromising specimen integrity.

**MATERIALS AND METHODS**

**Patient Selection and Specimen Acquisition**

This prospective study was approved by the Institutional Review Board (protocol: 2012P001358). A team of pathologists, thoracic surgeons, and radiologists developed a workflow to image surgical lung resection specimens using micro-CT at a tertiary care hospital.

Between March 2015 and April 2016, 21 patients (45% female; mean age, 67.5 ± 9.2 years; age range, 46–82 years) with a presumptive diagnosis of lung cancer for whom surgical resection was clinically indicated were consented for specimen imaging. Surgical resections proceeded per standard of care. Following resection, specimens were placed in a sterile container (ClikSeal Specimen Container, 120cc, Medical Action Industries, Mechanicsville, Virginia; DeRoyal Specimen Plastic Jar with Lid, 475cc, DeRoyal, Powell, Tennessee) by the surgeon in the operating room. Choice of container was based on specimen size.

**Image Acquisition**

Specimens were transported from the operating room to a micro-CT scanner located in the hospital pathology laboratory. No sample preparation or fixation was performed. Specimen containers with the enclosed samples were placed directly into the micro-CT scanner, with the lid remaining closed during image acquisition. A Skyscan 1275 scanner (Bruker microCT, Kontich, Belgium) with a 1-mm aluminum filter was used for smaller specimen containers, whereas a XT H 225 scanner (Nikon Metrology Inc, Brighton, Michigan) with a 1-mm beryllium filter was used for larger specimen containers.

Imaging parameters were chosen based on manufacturer instructions as well as nomograms derived from prior experiments on pig lung (I.S.M. et al, unpublished data, 2015). Resulting voxel size was directly proportional to source-to-object distance. Increasing the number of projections is known to decrease image noise but increase scan time; therefore, we chose to obtain the maximum number of projections possible within the time available for imaging in each instance. Time required for image acquisition was recorded and radiation dose to the specimen was estimated using manufacturers’ instructions and a web-based calculator.

**Histopathology and Molecular Genetic Studies**

After imaging, specimens were delivered to the pathology laboratory for frozen section if deemed clinically necessary by the operating surgeon. In such cases, frozen sectioning was performed while the patient remained on the operating room table. Following completion of resection, routine pathologic workup proceeded per standard of care, including fixation, gross assessment, and selection of clinically relevant tissue blocks for sectioning, staining, and microscopic assessment. If indicated for clinical decision-making, molecular analysis was performed. Molecular testing included SNaPshot assays and gene fusion assays (Archer, Boulder, Colorado), both of which used anchored multiplex polymerase chain reaction. Reports of histopathologic features (diagnosis, lesion size, relationship to margins) and molecular analysis rendered as part of clinical care were reviewed and abstracted.

After completion of the study, a thoracic pathologist (L.P.H., fellowship trained, 8 years of experience) performed a blinded review of histopathology. Hematoxylin and eosin slides and immunohistochemistry slides from the 22 imaged specimens were compared to slides from 22 nonimaged lung resection specimens processed by pathology during the same time frame (control group) and matched for specimen type and histology. Slides were assessed for artifacts, potential sequelae from micro-CT imaging, and adequacy for clinical interpretation.

**Image Analysis**

A thoracic radiologist (F.J.F., fellowship trained, 8 years of experience) blinded to the pathology report evaluated micro-CT images retrospectively on a research workstation using ImageJ, in tandem with preoperative conventional chest CT images. Micro-CT images were assessed in multiple reconstruction planes and as a 3D volume-rendered data set. The radiologist and a research assistant (F.M.T.) determined maximum target lesion diameter and nearest distance to the surgical margin in consensus using electronic calipers, with the surgical margin defined by the staple line. The presence of imaging artifacts was recorded. Findings were correlated to the operative report.

**Outcomes**

The primary outcomes of this study were (1) rate of specimen adequacy for histopathologic and molecular analysis and (2) time required for micro-CT imaging. Secondary outcomes were (1) assessment of micro-CT image quality and (2) agreement of micro-CT measurements with pathology findings.

**Statistical Analysis**

Descriptive statistics were reported as mean ± SD and range for normally distributed data, and as median, interquartile range (IQR), and range for nonnormally distributed data, where appropriate. Normality was determined using the Kolmogorov-Smirnov test. Limits of agreement analysis was performed per the Bland-Altman method to evaluate agreement between micro-CT and pathology with regard to measurement of lesion size and distance to the nearest surgical margin. Limits of agreement results were reported as mean difference and 95% CIs of difference. Statistical analysis was performed using STATA software (version 13.0, StataCorp, College Station, Texas) and Microsoft Excel 2015 (Redmond, Washington).

**RESULTS**

**Specimen Characteristics and Image Acquisition**

A total of 22 surgical specimens from 21 patients (45% female) were obtained. Mean patient age was 67.5 ± 9.2 years (range, 46–82 years). Specimens included 11 wedge resections (50%), 9 lobectomies (40.9%), and 2 pneumonectomies (9.1%; Table 1). One patient underwent 2 lung resections at 2 separate time points, and both specimens were included. Median size of the surgical specimens was 114 mm (IQR, 91–158 mm; range, 35–240 mm).

Mean image acquisition time (time required to generate the electronic data set, not to include image reconstruction
and analysis) was 13 ± 6 minutes. Most of the specimens were imaged with the XT H 225. Spatial resolution ranged from 29 to 95 μm, and median estimated radiation dose was 0.43 Gy. Additional technical parameters are summarized in Table 2.

Intraoperative frozen section was performed on 21 of 22 specimens (95.5%) following micro-CT imaging. Intraoperative requests included histologic diagnosis (n = 14; 66.7% of all frozen sections), margin assessment (n = 8; 38.1%), and nodal evaluation (n = 4; 19.0%; note that in some cases, multiple requests were made).

**Pathology Findings**

A final histopathologic diagnosis was established for all lesions, and 18 lesions were malignant (81.8%; Table 1). The median pathologically determined lesion size was 20 mm (IQR, 15–32 mm; range, 6–125 mm). Molecular snapshot analysis was successfully performed on 11 specimens (50%), and molecular fusion assays on 10 specimens (45.5%), with analysis was successfully performed on 11 specimens (50%)

**Imaging Findings and Agreement With Pathologic Measurements**

The target lesion was readily identified in 12 of 22 scans (54.5%). Surgical chain sutures presented as linear foci of high attenuation in the periphery of the specimen and did not preclude target lesion assessment (Figure 1). The following artifacts obscured the target lesion in 10 of 22 instances (45.5%): insufficient air-soft tissue contrast due to atelectasis (6 of 10; 60%), motion generated by specimen deflation during image acquisition (2 of 10; 20%; Figure 2), and suboptimal detector calibration (2 of 10; 20%). The incidence of these artifacts organized by specimen type (eg, wedge resection, lobectomy, pneumonectomy) is presented in Table 3.

Median size of target lesions measured on micro-CT images was 14.7 mm (IQR, 12.8–73.0 mm; range, 6.4–120.8 mm). Comparison with pathologically derived lesion size revealed a mean difference of −2.8% (limits of agreement, −14.5% to 20.0%; Figure 3, A). Distance to the nearest surgical margin could be measured in 10 of 12 scans (83.3%). None of the 10 specimens (8.5–15.1 mm; range, 1–34 mm). Mean difference between margin distance on imaging and pathology was −0.5 mm (limits of agreement, −4.4 to 3.4 mm; Figure 3, B). The difference in margin distance between imaging and pathology did not exceed 4 mm for any specimen, and it was no more than 2 mm for specimens in which the pathologically confirmed margin distance was less than 30 mm.

In addition to the ability to assess lesion size and surgical margins, 3D analysis of the whole resection specimen was also useful to localize lesions of interest in preparation for microscopic evaluation. This is best illustrated by a subcentimeter pure ground-glass nodule (Figure 4). This noninvasive primary lung adenocarcinoma had been bracketed preoperatively by percutaneously placed gold fiducial markers to facilitate resection. The lesion was not identified on initial evaluation of the fixed specimen, and as a result no markers to facilitate resection. The lesion was not identified preoperatively by percutaneously placed gold fiducial markers to facilitate resection. The lesion was not identified preoperatively by percutaneously placed gold fiducial markers to facilitate resection.

**Table 2. Image Acquisition Parameters**

| Micro–computed tomography scanner, No. (%) | XT H 225 (Nikon) | 15 (68) |
| Tube current, μA | 265 ± 75 (142–400) |
| mean ± SD (range) | 63.6 ± 5.7 (50–70) |
| Estimated radiation dose, Gy, median (IQR; range) | 0.43 (0.18–0.53; 0.08–9.46) |
| Image acquisition time, min, mean ± SD (range) | 13 ± 6 (7–32) |
| Image resolution, μm, mean ± SD (range) | 55 ± 20 (23–95) |
| Distance between source and sample, cm, mean ± SD (range) | 37 ± 20 (10–75) |
| Number of projections, median (IQR; range) | 872 (600–1200; 528–2400) |
| Number of frames per projection, median (IQR; range) | 4 (3–4; 2–4) |
| Exposure time per projection, ms, median (IQR; range) | 250 (217–250; 137–250) |

**Abbreviation:** IQR, interquartile range.

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**Table 1. Characteristics of Patients (n = 21) and Lesions (n = 22)**

| Age, y, mean ± SD (range) | 68 ± 9 (46–82) |
| Sex, No. (%) | Male 12 (57) |
| | Female 9 (43) |
| Diagnosis, No. (%) | Malignant 18 (82) |
| | Lung adenocarcinoma 10 (45) |
| | Lung squamous cell carcinoma 5 (23) |
| | Melanoma metastasis 1 (5) |
| | Pancreatic adenocarcinoma metastasis 1 (5) |
| | Colon adenocarcinoma metastasis 1 (5) |
| | Benign 4 (18) |
| | Granuloma 2 (9) |
| | Elastic scar 1 (5) |
| | Metaplastic bone malformation 1 (5) |
| Procedures, No. (%) | Wedge resections 11 (50) |
| | Lobectomies 9 (41) |
| | Pneumonectomies 2 (9) |
| Lesion morphology on preoperative chest computed tomography, No. (%) | Solid 13 (59) |
| | Part solid 5 (23) |
| | Pure ground glass 3 (14) |
| | Cavitary mass 1 (5) |
Lastly, high-resolution micro-CT images revealed morphologic features that were not readily appreciated on conventional CT images. This is illustrated by a granuloma, which contained a focal central calcification on micro-CT images and had a smooth margin. Although both features suggest a benign etiology, they were not appreciated on conventional CT images (Figure 5). In malignant lesions, the spiculations associated with invasive lung cancers (Figure 6) were also more readily apparent on micro-CT images compared with conventional CT.

**DISCUSSION**

This pilot study demonstrated the feasibility of perioperative micro-CT imaging of fresh surgical lung specimens. We were able to integrate micro-CT into the clinical workflow without affecting subsequent routine pathologic and molecular analysis. Additionally, micro-CT could localize the majority of target lesions, determine the distance to the nearest surgical margin with high accuracy, and provide high-resolution whole-lesion morphologic data.

The primary objective of this pilot study was to evaluate the potential risk of performing micro-CT on clinical specimens, such as compromising specimen integrity prior to fixation and routine pathologic analysis, either due to delay in processing or damage from ionizing radiation. These factors were of particular concern for molecular analysis because minimizing time from resection to tissue fixation is paramount for reducing the degradation of cellular RNA and permitting analysis of genetic alterations.\(^\text{18}\)

Our results demonstrated that all imaged specimens were adequate for subsequent histopathologic analysis, with equivalent histologic quality compared with a control group of nonimaged specimens. Importantly, imaging did not impede the ability of RNA-based molecular snapshot and fusion assays to genetically subclassify tumors. The potential for micro-CT to damage fresh lung specimens has not previously been evaluated, given that all previous micro-CT work involving human lung tissue used permanent specimen fixation, such as glutaraldehyde, and did not involve subsequent molecular analysis.\(^\text{11,12}\)

Time required for image acquisition was 13 minutes on average, suggesting that this noninvasive 3D tissue analysis may be compatible with the intraoperative setting. Although we did not specifically investigate how to shorten image acquisition time, some good-quality scans required less than 8 minutes, indicating the feasibility of time-saving modifications such as obtaining fewer projections. Moreover, having micro-CT guide frozen section tissue selection by identifying the lesion location within the specimen could result in reduced operating room time, provided that real-time image interpretation can be arranged. This was highlighted by a scan that demonstrated the location of a noninvasive lung adenocarcinoma bracketed by gold fiducial markers within the fresh resection specimen, whereas this lesion could not be readily identified by pathology.

Multiplanar reformats and 3D renderings of good-quality micro-CT images facilitated localization of the target lesion within nonfixed lung resection specimens. The degree of discrepancy between lesion size measurement by micro-CT and pathology (up to 14% of lesion diameter) and the trend toward size overestimation with micro-CT were in line with a prior study of breast lumpectomy specimens.\(^\text{13}\)

This discrepancy, as previously postulated, was possibly attrib-
Figure 3. Bland-Altman plots demonstrate agreement between micro–computed tomography (micro-CT) and pathology for the measurement of lesion size (A) and distance from lesion to nearest margin (B). The solid line indicates mean difference, and dashed lines represent the 95% limits of agreement.

Figure 4. Micro–computed tomography image (A) of a fresh wedge resection specimen of a 76-year-old woman demonstrates the location of a ground-glass nodule (arrow). Two gold fiducial markers bracketing the lesion had been placed percutaneously prior to resection to facilitate intraoperative lesion localization by the surgeon and serve as landmarks indicating lesion location. Also noted are surgical sutures (circle). The ground-glass nodule was not grossly identifiable in the specimen, and therefore was not initially submitted for microscopic examination. The lesion was only identified after additional sections were submitted for microscopy, which resulted in a delay in the final diagnosis. A representative nonmatched section through the lesion (B) demonstrates adenocarcinoma in situ (hematoxylin-eosin, original magnification ×20).

| Specimen Type     | Target Lesion Visualization, No. (%) | Insufficient Air-Tissue Contrast | Motion Generated by Specimen Deflation | Suboptimal Detector Calibration | Total, No. (%) |
|-------------------|--------------------------------------|----------------------------------|----------------------------------------|---------------------------------|----------------|
| Wedge resection   | 6 (54.5)                             | 3 (27.3)                         | 2 (18.2)                               | 0 (0)                           | 11 (100)       |
| Lobectomy         | 4 (44.4)                             | 3 (33.3)                         | 0 (0)                                  | 2 (22.2)                        | 9 (100)        |
| Pneumonectomy     | 2 (100)                              | 0 (0)                            | 0 (0)                                  | 0 (0)                           | 2 (100)        |
utable to the fact that a 3D rendering derived from micro-CT images could more readily demonstrate the maximal lesion diameter, or due to tissue shrinkage during fixation. In 10 of the 12 scans that clearly demonstrated the target lesion, micro-CT was also able to determine the distance to the nearest surgical margin—a capability not previously studied—and these measurements were within 4 mm of those specified in the final pathology report. The maximum discrepancy between micro-CT and pathology with regard to margin assessment was even smaller when the distance to the nearest margin was less than 3 cm, indicating higher agreement in instances requiring greater precision. As with lesion size measurements, it is possible that margin distances derived from 3D data sets were actually more accurate than 2D pathology measurements.

The ability of micro-CT to localize target lesions within a specimen, identify the nearest surgical margin, and provide detailed morphologic data suggests potential applications

Figures 5 and 6 illustrate these findings. Figure 5 shows an axial non-contrast-enhanced conventional computed tomography image (A) in a 72-year-old man demonstrating a persistent right upper lobe solid nodule (arrow). Smoking history and apparent spiculation raised the concern for lung cancer and triggered resection. Micro-computed tomography image (B) of the fresh wedge resection specimen demonstrates a solid lesion (arrow) with smooth margins and a punctate central calcification (arrowhead). Note the streak artifact associated with surgical sutures (circles). Histopathology revealed a granuloma related to histoplasmosis.

Figure 6 depicts an axial contrast-enhanced conventional computed tomography image (A) in a 68-year-old man demonstrating a left upper lobe solid, spiculated nodule (arrow). Three-dimensional rendering of micro-computed tomography images of the fresh wedge resection specimen (B) better depicts the spiculated margins of this lesion (arrow), an invasive lung adenocarcinoma. Note the streak artifact associated with surgical sutures (circle).
that intersect with 3 evolving trends in thoracic oncology. First, lung cancer screening is likely to increasingly uncover small or subsolid lesions that warrant resection but are difficult to identify by tactile or visual inspection during intraoperative frozen section or even during gross evaluation for permanent sections, as demonstrated in Figure 4. In these instances, micro-CT performed immediately after resection might help direct specimen sectioning and thus expedite analysis, especially when metallic fiducial markers were placed preoperatively and serve as reference landmarks. Second, the movement toward tissue-conserving sublobar resection requires meticulous attention to surgical margins, particularly in light of prior studies showing positive margins following lung cancer resection in more than 5% of resections. Histologic sectioning alone, by only sparsely sampling the specimen, could miss important features. The macroscopic tissue context provided by a 3D rendering of surgical specimens can highlight areas warranting focused pathologic analysis, such as the part of the tumor closest to the surgical margin, thereby directing the pathologist toward the histologic sections most likely to influence intraoperative decision-making. Third, the whole-lesion morphologic data contained in high-resolution (<100 μm) micro-CT images could be used for radiogenomic analysis and possibly inform efforts to extract additional features from routine conventional CT images. As such, micro-CT can be considered an interdisciplinary tool to optimize integrated intraoperative patient care, especially for the assessment of subsolid nodules. Both pathologists and radiologists can contribute their respective skill sets given that interpretation of micro-CT images is akin to interpretation of conventional CT images.

This pilot study had several limitations that warrant consideration. First and foremost, artifacts obscured the target lesion in a number of scans. Although suboptimal lesion-to-tissue contrast was occasionally reported in breast target lesions in a number of scans. Although suboptimal lesion-to-tissue contrast was occasionally reported in breast target lesions in a number of scans. Although suboptimal lesion-to-tissue contrast was occasionally reported in breast target lesions in a number of scans. Although suboptimal lesion-to-tissue contrast was occasionally reported in breast target lesions in a number of scans. Although suboptimal lesion-to-tissue contrast was occasionally reported in breast target lesions in a number of scans. Although suboptimal lesion-to-tissue contrast was occasionally reported in breast target lesions in a number of scans. Although suboptimal lesion-to-tissue contrast was occasionally reported in breast target lesions in a number of scans. Although suboptimal lesion-to-tissue contrast was occasionally reported in breast target lesions in a number of scans. Although suboptimal lesion-to-tissue contrast was occasionally reported in breast target lesions in a number of scans. Although suboptimal lesion-to-tissue contrast was occasionally reported in breast target lesions in a number of scans. Although suboptimal lesion-to-tissue contrast was occasionally reported in breast target lesions in a number of scans. Although suboptimal lesion-to-tissue contrast was occasionally reported in breast target lesions in a number of scans. Although suboptimal lesion-to-tissue contrast was occasionally reported in breast target lesions in a number of scans. Although suboptimal lesion-to-tissue contrast was occasionally reported in breast target lesions in a number of scans. Although suboptimal lesion-to-tissue contrast was occasionally reported in breast target lesions in a number of scans. Although suboptimal lesion-to-tissue contrast was occasionally reported in breast target lesions in a number of scans. Although suboptimal lesion-to-tissue contrast was occasionally reported in breast target lesions in a number of scans. Although suboptimal lesion-to-tissue contrast was occasionally reported in breast target lesions in a number of scans. Although suboptimal lesion-to-tissue contrast was occasionally reported in breast target lesions in a number of scans. Although suboptimal lesion-to-tissue contrast was occasionally reported in breast target lesions in a number of scans. Although suboptimal lesion-to-tissue contrast was occasionally reported in breast target lesions in a number of scans. Although suboptimal lesion-to-tissue contrast was occasionally reported in breast target lesions in a number of scans. Although suboptimal lesion-to-tissue contrast was occasionally reported in breast target lesions in a number of scans. Although suboptimal lesion-to-tissue contrast was occasionally reported in breast target lesions in a number of scans. Although suboptimal lesion-to-tissue contrast was occasionally reported in breast target lesions in a number of scans. Although suboptimal lesion-to-tissue contrast was occasionally reported in breast target lesions in a number of scans. Although suboptimal lesion-to-tissue contrast was occasionally reported in breast target lesions in a number of scans. Although suboptimal lesion-to-tissue contrast was occasionally reported in breast target lesions in a number of scans. Although suboptimal lesion-to-tissue contrast was occasionally reported in breast target lesions in a number of scans. Although suboptimal lesion-to-tissue contrast was occasionally reported in breast target lesions in a number of scans.

In conclusion, micro-CT of fresh surgical lung specimens is feasible and has the potential to aid in the evaluation of the size and location of lesions within resection specimens, as well as distance to surgical margins, all without compromising specimen integrity. Future studies are required to investigate methods to reduce imaging artifacts and prospectively evaluate the role of micro-CT in intraoperative decision-making.

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