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Duke Clinical Imaging Physics Group

Thermal Modeling of Diagnostic X-ray Tubes: Retrospective Monitoring and Prospective Protocol Evaluation

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PURPOSE

To retrospectively identify potential x-ray tube overheating events and to prospectively design protocols and workflow strategies to mitigate heat-related risks that can lead to tube downtime and workflow disruption.

INTRODUCTION

X-ray tube overheating can cause equipment downtime, disrupt clinical workflow, and delay patient care. If imaging volumes, exam complexity, or patient size increase, objective tools are needed to assess thermal risk and guide operational planning.

We developed a modeling framework that combines DICOM exposure data with manufacturer heating and cooling curves to retrospectively evaluate anode and housing heat loading and prospectively simulate the thermal demands of imaging protocols. This approach provides a practical method to identify high-risk workflows, support safe tube operation, and assess whether equipment can accommodate anticipated clinical workloads.

METHODS

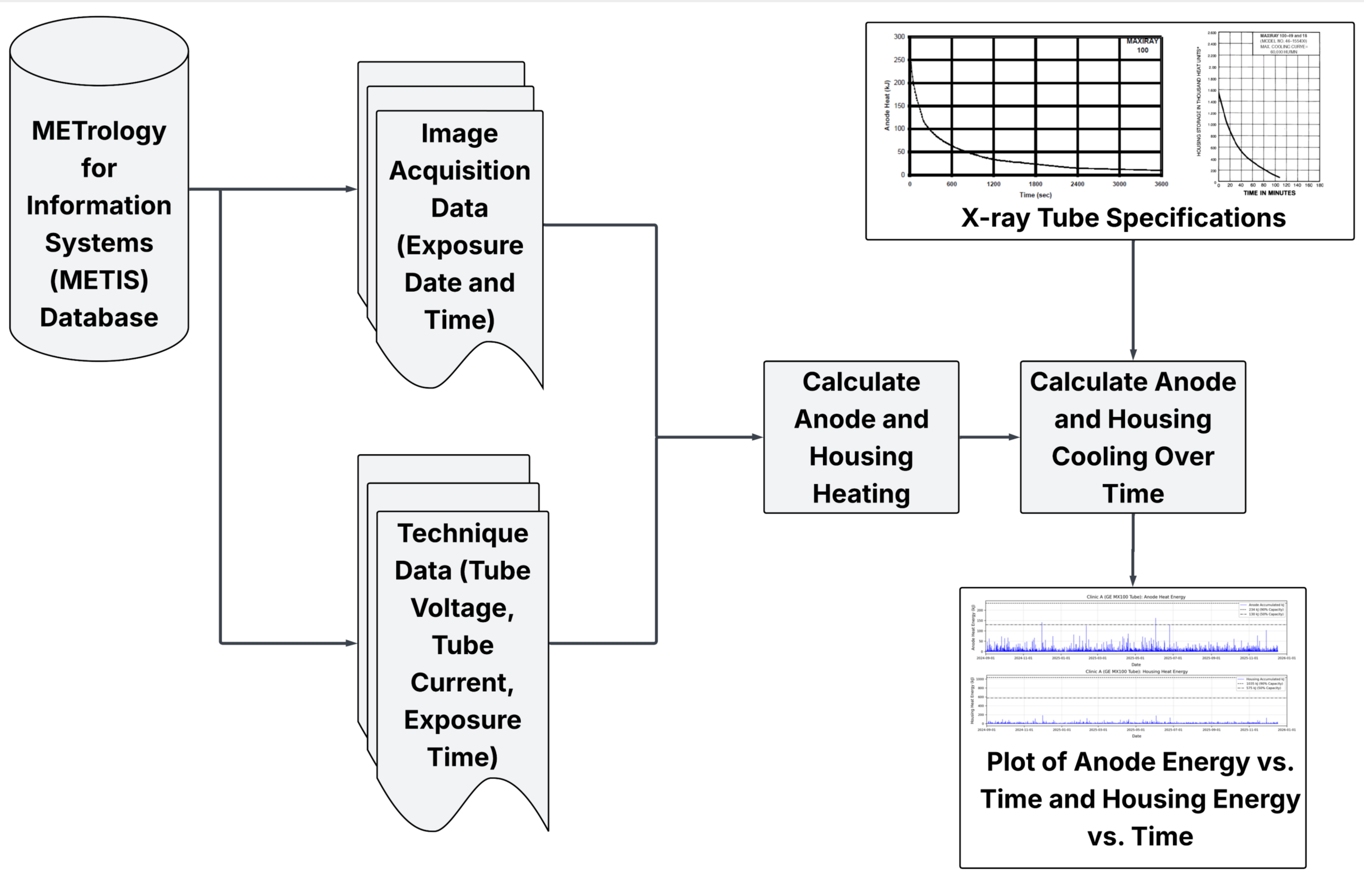

Figure 1. Flowchart depicting the simulation framework used for this study.

A 15-month exposure timeline was constructed using acquisition and technique parameters extracted from DICOM metadata. Four x-ray tubes were modeled using manufacturer-specified tube heating and cooling curves. See Table 1.

Heat deposition and dissipation were modeled on a per-second basis to estimate cumulative anode and housing heat load over time. Retrospective analysis identified periods exceeding 50% and 90% of maximum anode or housing heat capacity.

The model was also used prospectively to simulate a high-mAs five-view lumbar spine examination and evaluate the effects of examination spacing and repeat images on thermal loading and maximum safe throughput.

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METHODS

Table 1. Modeled x-ray tubes and manufacturer-specified anode and housing heat contents.

Clinic	Clinic Type	Manufacturer	Vendor Model Number	Anode Heat Content (kJ)	X-ray Tube Assembly Heat Content (kJ)
A	Inpatient	GE Healthcare	MX100	260	1,100
B	Primary Care	GE Healthcare	MX100	260	1,100
C	Urgent Care	TOSHIBA TUBE	E7252	210	900
D	Primary Care	Rotanode	E7254	285	950

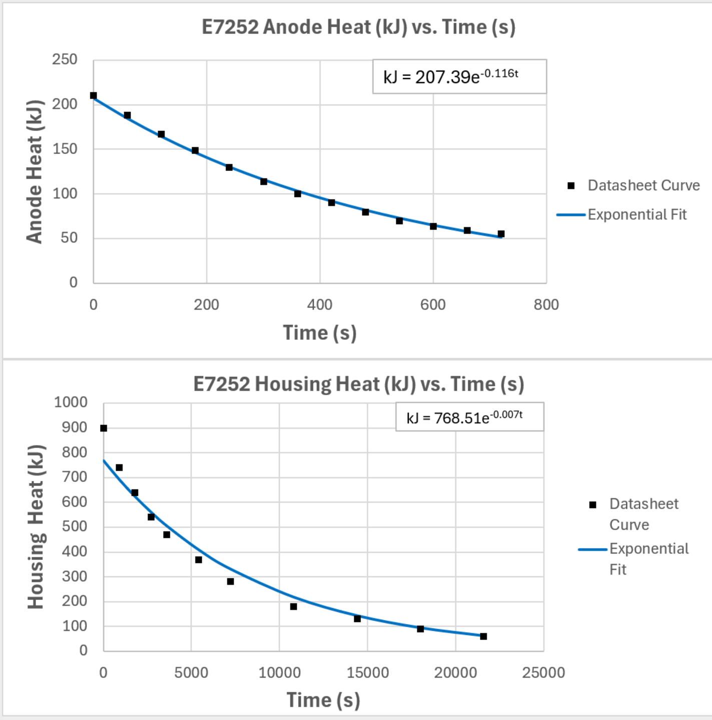

Figure 2. Example of anode and housing cooling curve models for one clinic (Clinic C). Anode and housing cooling curves were modeled using tube manufacturer's technical specifications. An exponential model was chosen since it provided the best fit.

RESULTS

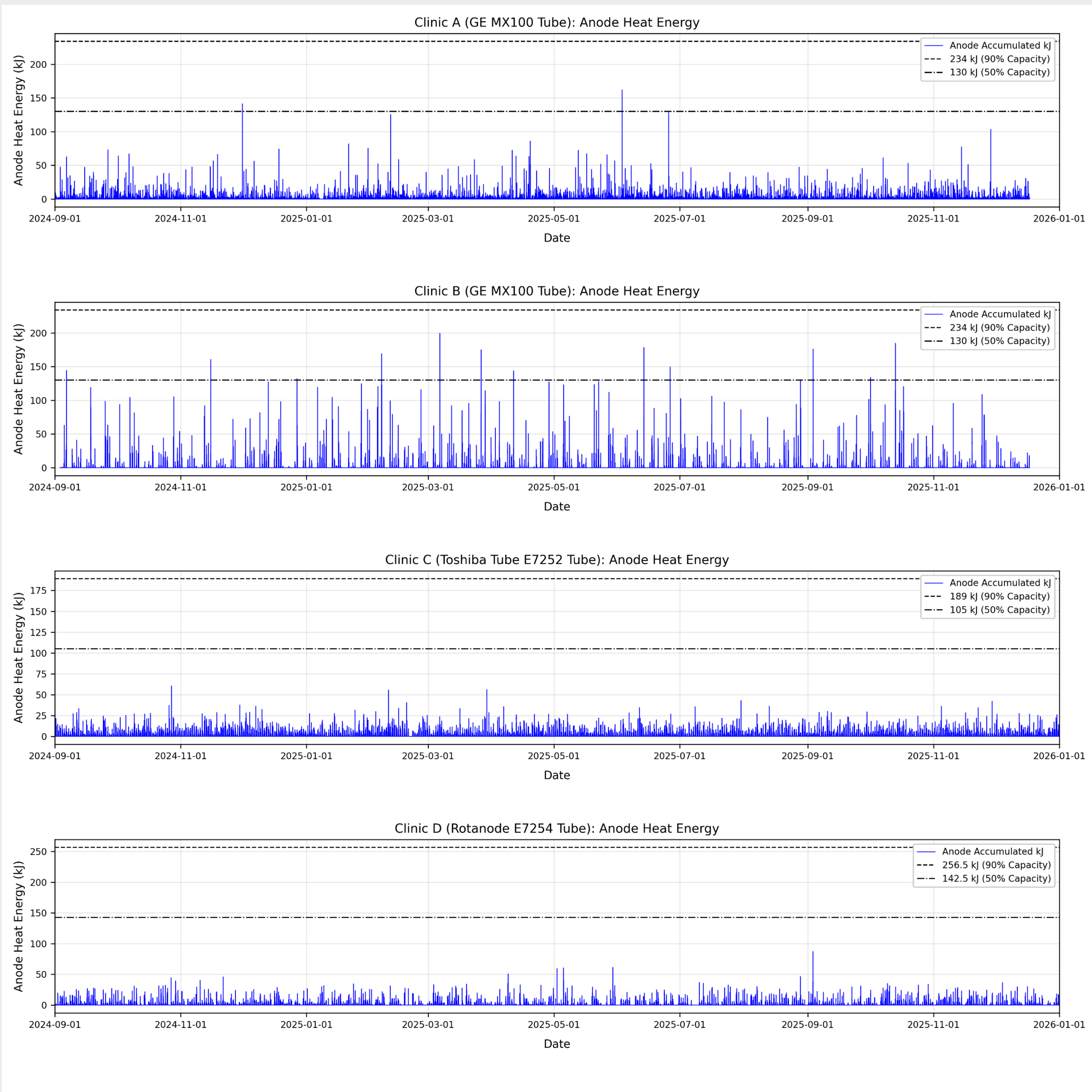

Figure 3. Retrospective anode heat loading over 15 months. Anode heat energy (kJ) over a fifteen-month period for four x-ray tubes calculated using technique data extracted from DICOM headers. The simulation applied each manufacturer's x-ray cooling curve models to compute anode heat on a second-by-second basis. The horizontal dashed lines indicate the 50% and 90% anode heat capacity thresholds. Anode heat load exceeded the 50% threshold on 28 occasions during the 15-month period across all 4 sites. The 90% anode heat threshold was never exceeded.

RESULTS

Figure 4. Retrospective housing heat loading over 15 months. While each tube housing has a slower heat dissipation rate than the tube anode, the larger heat reservoir of each housing, due to the cooling oil bath and larger mass of housing metals, and lag time due to heat transfer reduces the intensity of heat loading incidents compared to the anode. Thus, housing thermal load is not expected to be a limiting factor in clinical practice or in prospective protocol simulations.

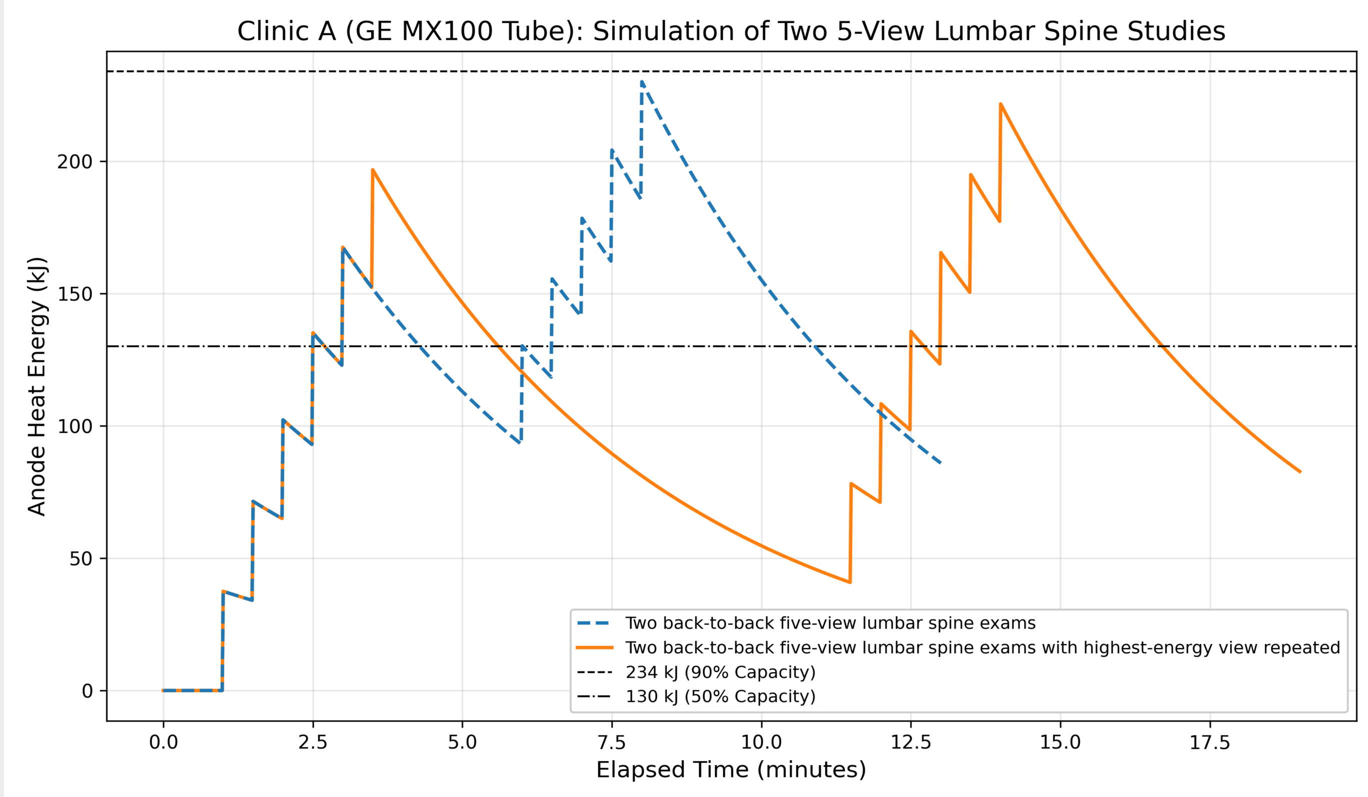

Figure 5. Prospective worst-case simulation of consecutive lumbar spine examinations. Two back-to-back five-view lumbar spine examinations were simulated using clinical kV settings, 500 mAs exposures, and 30-second intervals between views. A minimum interval of 3 minutes between examinations was required to remain below the 90% anode heat capacity threshold. When the highest-energy view was repeated once (orange curve), the minimum interval between examinations required to remain below the 90% anode heat capacity threshold increased from 3 to 8 minutes.

CONCLUSIONS

An x-ray tube heating model was developed to retrospectively assess thermal loading and prospectively evaluate protocol design. Retrospective analysis identified occasional periods of elevated anode heat load but no instances exceeding the 90% threshold. Prospective simulations established minimum examination intervals required to maintain safe operating conditions. This framework can be used to establish practical limits on the patient population that can be successfully imaged on various types of equipment. It also provides a tool to identify thermally demanding workflows, guide protocol design, and reduce the risk of tube overheating and associated equipment downtime.