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Harry E. Martz
G. Patrick Roberson
Karin Hollerbach
Clinton M. Logan
Elaine Ashby
Richard Bernardi

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Computed Tomography of Human Joints and Radioactive Waste Drums

Harry E. Martz, G. Patrick Roberson, Karin Hollerbach,
Clinton M. Logan, Elaine Ashby and Richard Bernardi[1]

Lawrence Livermore National Laboratory
7000 East Ave., Livermore, CA 94550

Abstract. X- and gamma-ray imaging techniques in nondestructive evaluation (NDE) and assay (NDA) have seen increasing use in an array of industrial, environmental, military, and medical applications. Much of this growth in recent years is attributed to the rapid development of computed tomography (CT) and the use of NDE throughout the life-cycle of a product. Two diverse examples of CT are discussed. (1) Our computational approach to normal joint kinematics and prosthetic joint analysis offers an opportunity to evaluate and improve prosthetic human joint replacements before they are manufactured or surgically implanted. Computed tomography data from scanned joints are segmented, resulting in the identification of bone and other tissues of interest, with emphasis on the articular surfaces. (2) We are developing NDE and NDA techniques to analyze closed waste drums accurately and quantitatively. Active and passive computed tomography (A&PCT) is a comprehensive and accurate gamma-ray NDA method that can identify all detectable radioisotopes present in a container and measure their radioactivity.

INTRODUCTION

Traditionally, NDE has been viewed only as an end-product inspection tool. The traditional view does not take advantage of the full economic benefit that NDE provides. NDE can ensure/improve safety, shorten the time between product conception and production, and help reduce waste. Examples include new material and process development; raw materials acceptance; process monitoring and control (1); finished product and in-service inspection; and retirement for cause, disposal, and reuse. Therefore, NDE is increasingly being used throughout the life-cycle management of products (2, 3).

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[1] Permanent address Bio-Imaging Research, Inc., 425 Barclay Blvd., Lincolnshire, IL 60069.

LIFE CYCLE APPLICATIONS OF COMPUTED TOMOGRAPHY

This section provides two examples of how different computed tomography methods are applied. One is applied early in the life cycle to study materials for human joint prosthetics; the other at the end of the life cycle for radioactive waste disposal.

Human Joints

Human joints are commonly replaced in cases of damage from traumatic injury, rheumatoid diseases, or osteoarthritis. Frequently, prosthetic joint implants fail and must be surgically replaced by a procedure that is far more costly and carries a higher mortality rate than the original surgery. Poor understanding of the loading applied to the implant leads to inadequate designs and ultimately to failure of the prosthetic (4).

LLNL's approach to prosthetic joint design offers an opportunity to evaluate and improve joints before they are manufactured or surgically implanted. The modeling process begins with computed tomography data (Figure 1). The CT data are used to segment the internal tissues as shown in Figure 2 (5). A three-dimensional surface of each joint structure of interest is created from the segmented data set (Figure 3). An accurate surface description is critical to the validity of the model. The

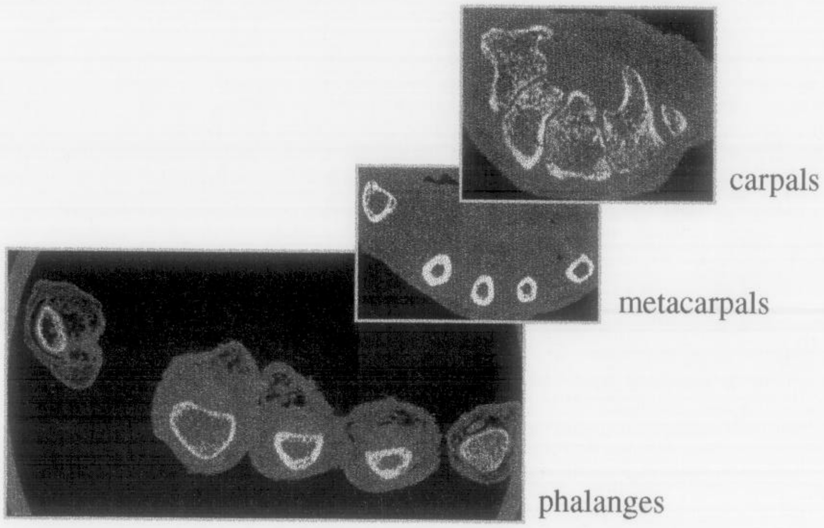

FIGURE 1. Representative x-ray CT images for different locations of a harvested women's right hand. The data were acquired by a linear-array CT scanner LCAT with 160x160x160-μm^3 voxels. The entire data set contains 1084 slices over ~17 cm.

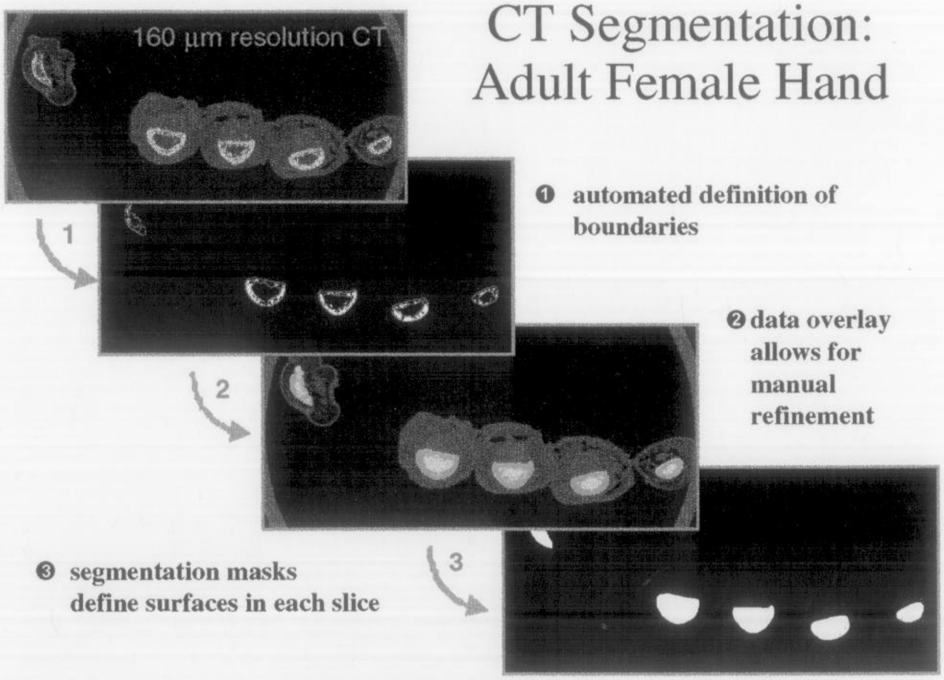

FIGURE 2. From left to right: One representative CT slice. Automatically defined boundaries for this CT slice. Semi-automated segmentation results overlaid onto its CT slice. Final segmentation results for this slice. After each of the 1084 slices is segmented they are investigated for interconnectivity and result in a 3D-volume segmentation of the women's hand.

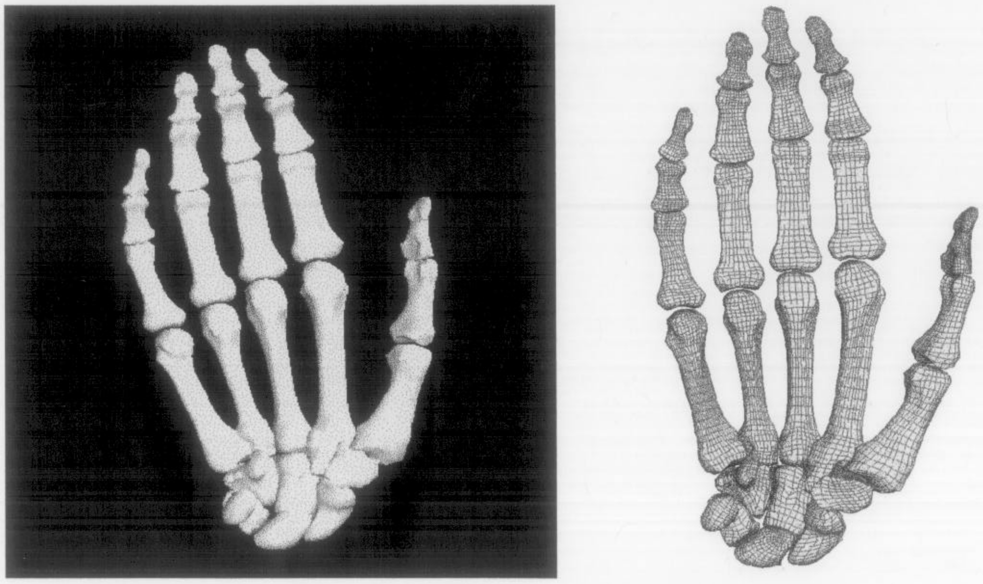

FIGURE 3. Left: A 3D surface-rendered image of the bone structure from the CT data of the women's hand. Right: 3D hexahedral finite-element mesh of the segmented bone structure.

marching cubes algorithm (6) is used to create polygonal surfaces that describe the 3D geometry of the structures (typically bone in the CT data) identified in the scans. Each surface is converted into a 3D volumetric, hexahedral finite-element mesh that captures its geometry. The resultant meshed bone structure of the hand is shown in Figure 3. Boundary conditions determine initial joint angles and ligament tensions as well as joint loads. Finite element meshes are combined with boundary conditions and material models. The analysis consists of a series of computer simulations of human joint and prosthetic joint behavior.

Computational analysis can reveal regions where the joint design can be improved for better performance and longevity, prior to expensive manufacturing, lab testing, and clinical evaluation. Computational analyses provide qualitative data in the form of scientific visualization and quantitative results such as kinematics and stress-level calculations (Figure 4). In human joints, these calculations help us to understand what types of stresses occur in daily use of hand joints. This provides a baseline for comparison of the stresses in the soft tissues after an implant has been inserted into the body. Similarly, the bone–implant interface stresses and stresses near the articular surfaces can be evaluated and used to predict possible failure modes.

Results from the finite element analysis are used to predict failure and to provide suggestions for improving the design. Multiple iterations of this process allow the implant designer to use analysis results to incrementally refine the model and improve the overall design. Once an implant design is agreed on, a prototype is made using computer-aided manufacturing techniques. The resulting implant can then be laboratory tested and put into clinical trials (7).

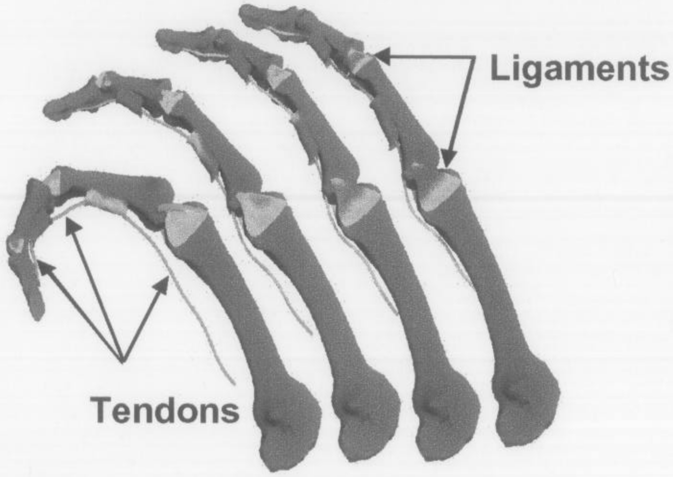

FIGURE 4. Three-dimensional model of the bone structure generated from CT scans of the women's index finger. The tendons and ligaments were added using prior knowledge. Different stages of finger flexion were studied by finite-element analysis. The different colors (purple/blue for low stress to red for high stress) within the tendons and ligaments indicate stresses during flexion.

Radioactive Waste Drums

Before drums of radioactive or mixed (radioactive and hazardous) waste can be properly stored or disposed of, the contents must be known. Hazardous and "nonconforming" materials (such as free liquids and pressurized containers) must be identified, and radioactive sources and strengths must be determined. Opening drums for examination is expensive mainly because of the safety precautions that must be taken. Current nondestructive methods of characterizing waste in sealed drums are often inaccurate and cannot identify nonconforming materials.[2]

Traditional NDA measurement errors are related to non-uniform measurement responses associated with unknown radioactive-source and waste-matrix-material distributions. These errors can be reduced by the application of imaging techniques that better measure the spatial locations of sources and matrix attenuations (9, 10, & 11). LLNL has developed an emerging gamma-ray NDA technology, called Active and Passive Computed Tomography (A&PCT), that identifies and accurately quantifies all detectable radioisotopes in closed containers of wastes, regardless of their classification: low level, transuranic or mixed waste.

The A&PCT technology uses two separate measurements. The first is an active interrogation of the drum using an external radioactive source(s) and the second is a passive measurement of the radioactive emissions from the drum. The results of these two measurements are combined to produce an attenuation corrected gamma-ray assay of the drum. The gamma-ray A&PCT method (12) involves: (1) Data acquisition (13); (2) Gamma-ray spectral analysis (14); and (3) Image reconstruction and assay (15).

Currently there are two operational single-detector A&PCT systems (12). One is located at LLNL and is used for research. The A&PCT technology has been transferred to a private sector company, Bio-Imaging Research, Inc. (BIR). BIR has built a mobile Waste Inspection Tomography (WIT) trailer that contains the other single-detector A&PCT technology (16, 17). The single-detector A&PCT system performance has been determined by several open and blind tests of well known radioactive sources within a variety of waste matrices in addition to several actual waste drums (12). At LLNL, WIT characterized drums that contained smaller containers with solidified chemical wastes; at RFETS,[3] WIT measured drums with low-density combustible matrices. At INEEL,[4] WIT characterized graphite-, glass-, and metal-matrix drums, lead-lined drums with combustibles, and very dense sludge drums. The Pu mass within these drums ranged from 1 to 70 grams (g).

Recently in order to increase throughput a multiple-detector A&PCT system was jointly developed by LLNL and BIR. This system uses a multiple collimated aperture

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[2] References for contemporary research, development, application and implementation of NDE and NDA systems are given in Proceedings of the NDA/NDE Waste Characterization Conferences (8).

[3] Rocky Flats Environmental Technology Site, Rocky Flats, CO.

[4] Idaho National Engineering and Environmental Laboratory, Idaho Falls, ID.

(*width*: 5.7 cm, *height*: 5.7 cm, *length*: 12.7 cm) with septa for six, high-purity Ge detectors (coaxial, ~65% relative efficiency) and six ^{152}Eu (~7 mCi) external radioactive sources. It is housed within a mobile land/sea container and is called the WIT container. The drum manipulator can handle up to 365 kg. The system can be operated in two different modes: (1) collimated gamma-ray scanner (CGS); or (2) A&PCT. The CGS mode is used to determine the A&PCT slice positions and data acquisition time. The acquisition time is a function of radioactivity and matrix absorption. A&PCT is used to accurately determine the isotopics of radioactive source(s) and their activity.

There is a well defined series of open and blind tests required of NDA measurement systems used to characterize transuranic waste prior to shipment to the Waste Isolation Pilot Plant (18, 19). A DOE sponsored performance demonstration program has built a set of well-known radioactive standards that can be inserted into a set of drums with well-known mock-waste matrices. We have used these drums and standards to determine the preliminary precision (% relative standard deviation), accuracy (% recovery) and bias for the six-detector A&PCT system.

Several 15 replicate studies were completed for three of the four required activity ranges (nominal compliance values are 0.1, 1.0 10, and 160 g weapons-grade Pu). The latter three ranges were measured by acquiring CGS and A&PCT data for three separate placements of radioactive standards within an empty-matrix drum. The standards had a total mass of 0.93, 9.3 and 33.48 g of ^{239}Pu positioned within the drum and required 4, 0.75, and 0.5 hours total (CGS and A&PCT) assay time, respectively. The performance results are summarized in Table 1.

TABLE 1. Nondestructive radio-assay performance requirements and measurement results.

	Nominal Radioactivity Range	**0.04 to 0.4 α-Ci**	**0.4 to 4.0 α-Ci**	**> 4.0 α-Ci**
	Nominal ^{239}Pu Amount	**0.94 grams**	**9.4 grams**	**150.4 grams**
	^{239}Pu Amount Measured	**0.93 grams**	**9.3 grams**	**33.48 grams**
Performance Requirements	Precision	15%	10%	5%
	Low Accuracy	50%	75%	75%
	High Accuracy	150%	125%	125%
	Low Bias	35%	67%	67%
	High Bias	300%	150%	150%
Measured Values	^{239}Pu Measured Average (15 reps)	0.84 grams	9.12 grams	32.33 grams
	Standard Deviation	0.09 grams	0.47 grams	1.40 grams
	% Relative Standard Deviation	9.45% (PASS)	5.02% (PASS)	4.17% (PASS)
	% Recovery	90.19% (PASS)	98.03% (PASS)	96.57% (PASS)
	Bias Low	40.63% (PASS)	67.3% (PASS)	67.07 (PASS)
	Bias High	294.37% (PASS)	149.7% (PASS)	149.93 (PASS)

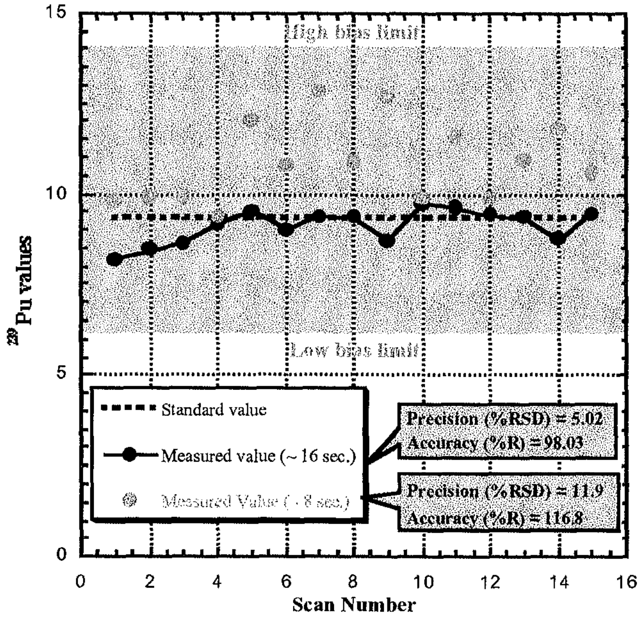

FIGURE 5. Six-detector A&PCT performance results for the empty-matrix drum with 9.3 g ^{239}Pu. This data reveals that a reduction of 2X in data acquisition time—16 and 8 sec. is the ray-sum acquisition time—nearly meets performance. New research shows that we meet performance.

Research is being investigated to increase throughput, for example, trading off accuracy and precision for decreased data acquisition time as shown in Figure 5. This data reveals that we can increase throughput by almost 2X for most drums and still be able to meet the performance requirements. New research has shown that on average we can meet the required performance for the three ranges in 2, 0.5 and 0.5 hours, respectively. This and other data reveals that we have a lower-limit data acquisition time of ~0.5 hour per drum. This is mainly limited by data transfer rates.

SUMMARY

The usefulness of CT for two diverse and challenging nondestructive characterization applications has been demonstrated. CT was useful in obtaining new insights into the human joint prosthetics. Nondestructive tomographic images are being employed in human joint implant design. Studies to date have shown the utility of this new high-spatial resolution CT data to improve performance and longevity, prior to expensive manufacturing, lab tests, and clinical evaluation. The use of active and passive CT in the nondestructive radioactive assay of waste drums has been able to meet the DOE performance requirements for disposal of transuranic waste at the Waste Isolation Pilot Plant, which just recently opened and has begun accepting waste.

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