

**INSTRUMENTATION REQUIREMENTS
OF DIAGNOSTIC
RADIOLOGICAL PHYSICISTS**



AAPM REPORT NO. 60

**INSTRUMENTATION REQUIREMENTS
OF
DIAGNOSTIC RADIOLOGICAL PHYSICISTS
(Generic Listing)**

Report of Task Group 4
Diagnostic X-Ray Imaging Committee

Members

Jane R Fisher, Chairperson
Pei-Jan Paul Lin, Co-chairperson
Priscilla Butler
Burton J Conway
Frank Ranallo
Raymond Rossi
Jeff Sheppard
Keith Strauss

October 1998

Published for the
American Association of Physicists in Medicine
by Medical Physics Publishing

DISCLAIMER: This publication is based on sources and information believed to be reliable, but the AAPM and the editors disclaim any warranty or liability based on or relating to the contents of this publication.

The AAPM does not endorse any products, manufacturers, or suppliers. Nothing in this publication should be interpreted as implying such endorsement.

Further copies of this report (\$10 prepaid) may be obtained from:

American Association of Physicists in Medicine
One Physics Ellipse
College Park, MD 20740-3843

International Standard Book Number: 1-888340-15-0

International Standard Serial Number: 0271-7344

©1998 by the American Association of Physicists in Medicine

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means (electronic, mechanical, photocopying, recording, or otherwise) without the prior written permission of the publisher.

Published by Medical Physics Publishing
4513 Vernon Blvd., Madison, WI 53705-4964

Printed in the United States of America

This report is dedicated to the memory of Raymond P. Rossi.

INSTRUMENTATION REQUIREMENTS OF DIAGNOSTIC RADIOLOGICAL PHYSICISTS

INTRODUCTION	1
A. Quality Control	1
B. Additional Required Equipment for Acceptance Testing	2
GENERIC LISTING	2
FILM PROCESSORS	2
A. Sensitometer	2
B. Densitometer	2
C. Thermometer	3
DOSIMETRY SYSTEM	3
A. General Purpose Meter	4
Uses	4
Range	4
Precision	4
Calibration Accuracy	4
Linearity	4
Energy Dependence	4
Exposure Rate Dependence	5
Leakage	5
Rate Meter	5
Amplification Gain	5
B. Area Survey Meter.....	5
Uses	5
Range	5
Precision	5
Calibration Accuracy.....	5
Linearity	6
Energy Dependence	6
Exposure Rate Dependence	6
Leakage	6
Rate Meter	6
Amplification Gain	6

C.	High Sensitivity Meter	6
	Uses	6
	Range	7
	Precision	7
	Calibration Accuracy.....	7
	Linearity..	7
	Energy Dependence	7
	Exposure Rate Dependence	7
	Leakage	7
	Rate Meter	7
	Amplification Gain.....	7
D.	Mammography Meter.....	8
	Uses	8
	Range	8
	Precision	8
	Calibration Accuracy.....	8
	Linearity	8
	Energy Dependence	8
	Exposure Rate Dependence	8
	Leakage	8
	Rate meter	9
	Amplification Gain.....	9
E.	CT Meter.....	9
	Uses	9
	Range	9
	Precision	9
	Calibration Accuracy.....	9
	Linearity..	9
	Energy Dependence	9
	Exposure Rate Dependence	10
	Leakage.....	10
	Rate Meter.....	10
	Amplification Gain.....	10
	Useful Features	10

INVASIVE TEST EQUIPMENT	10
A. High Voltage Divider/Measurement System	10
Basic Specifications	11
B. High Voltage Cables, Insulation Oils and Insulation Greases	11
C. mA/mAs Meter	12
D. Digital Multimeter	12
STORAGE OSCILLOSCOPE	13
A. Basic Analog System Configuration	13
B. Specifications: Analog	13
1. Horizontal	13
2. Vertical	14
3. Trigger	14
C. Environmental	14
D. Additional System Requirements for Digital	14
NON-INVASIVE TEST EQUIPMENT	15
A. kVp Test Devices	17
Basic Specifications	17
1. kVp Range	17
2. kVp Accuracy	17
3. kVp Resolution	18
4. kVp Reproducibility	18
Desirable Features	18
B. X-ray Exposure Timers	18
Basic Specifications	18
FOCAL SPOT EVALUATION TEST TOOLS	18
A. Star Patterns	18
B. Slit Camera	19
C. Pinhole	19
D. Resolution Bar Patterns	19
E. Alignment Stand	19
F. Power Magnifier with Graticule	19

CONVENTIONAL TOMOGRAPHY TEST TOOLS	19
A. Pinhole	19
B. Resolution	19
C. Slice Thickness/Cut Level	20
D. Accessories	20
PHANTOMS OR ATTENUATING MATERIALS	20
A. Attenuating Materials	20
1. Aluminum Filters	20
2. Copper Sheets	20
3. Lead Sheets	20
4. Acrylic/Tissue Equivalent BR-12	20
5. Acrylic	21
B. Phantoms	21
1. CT Phantoms for QC and Dosimetry	21
2. Mammography Phantom	21
C. Clinical Attenuation Phantoms (AAPM Report No. 31)	22
1. Modified ANSI Phantoms	22
a. Abdomen/Lumbar Spine	22
b. Skull	23
c. Extremity	24
d. Chest	25
2. CDRH LucAl Phantoms	26
a. CDRH LucAl Chest	26
b. CDRH LucAl Abdomen/Lumbar Spine	27
c. CDRH LucAl Fluoroscopy	28
3. DSA Phantoms	28
LEEDS TEST OBJECTS	29
FLUOROSCOPIC EVALUATION TEST TOOLS	29
A. High Contrast Resolution Mesh	29
B. Fluoroscopic Threshold Contrast Test Tool	29
C. Centering and Alignment Tool	29
D. Beam Restriction and Sizing Evaluation Device	30

RADIOGRAPHIC X-RAY AND LIGHT FIELD EVALUATION TEST TOOLS	30
A. Collimator Alignment Tool	30
B. Fluorescent Screen Strips	30
SCREEN/FILM CONTACT	30
Radiographic and Mammographic Wire Mesh	30
A. Radiographic	30
B. Mammographic	31
GRID ALIGNMENT	31
Grid Alignment Test Tool	31
VIDEO SYSTEM EQUIPMENT	31
A. Multisync Video Monitor	31
B. Video Level Meter	32
C. Pincushion Distortion Grid	33
D. Rotating Spoke Test Object	33
COMPUTER SYSTEMS (HARDWARE AND SOFTWARE)	34
A. Office PC Equivalent System: Hardware Selection	34
1. Apple Macintosh, IBM and IBM Compatible Platform	34
2. Laptop Personal Computer	34
B. Software Recommendations	35
C. Printer	35
MULTI-FORMAT CAMERAS	35
A. Video Test Pattern Generator	35
B. Video Test Pattern Tape	36
MISCELLANEOUS	37
BIBLIOGRAPHY	38

INSTRUMENTATION REQUIREMENTS OF DIAGNOSTIC RADIOLOGICAL PHYSICISTS

INTRODUCTION

The charge to TG#4 was to compile a list of equipment with recommended minimum specifications that can be used when purchasing test equipment for evaluation of radiographic and fluoroscopic x-ray units. This report is meant to be used by practicing medical physicists responsible for acceptance testing or quality control testing in diagnostic facilities. Some of the included equipment is meant to be used for quality control testing only, while others can be used for both quality control and acceptance testing. All results of any measurements should be interpreted by a qualified medical physicist,

The decision as to what equipment is needed by a facility will have to be determined on a case by case basis by the medical physicist. Choice will depend on the type of testing to be performed, type of equipment to be evaluated, intended user, and monetary constraints of the facility. Some equipment is much more sensitive to handling errors and exhibits larger dependence on setup geometry and beam energy than others. The physicist will require as a minimum the following equipment:

A. **Quality Control:**

1. Dosimetry System
2. Non-invasive kVp measurement system with digital readout
3. Aluminum for HVL determination
4. Attenuating materials/phantoms for evaluation of AEC, fluoroscopic ABC, and patient ESE
5. Focal spot test tool
6. Image evaluation test tools
7. Sensitometer, densitometer, and thermometer for processor evaluation
8. Grid and image receptor test tools

9. Light field/x-ray field alignment, positive beam limitation, and fluoroscopic alignment test tools
10. Tomographic performance test tools
11. DSA phantom
12. Computer system

B. Additional Required Equipment for Acceptance Testing:

1. Invasive test equipment
 - a. Voltage divider
 - b. mA/mAs meter
 - c. Digital Multimeter
 - d. Oscilloscope
2. Slit camera, stand and magnifier for focal spot measurement
3. Video system equipment
4. Video test pattern generators

GENERIC LISTING

FILM PROCESSORS

A. Sensitometer:

Dual color. single and dual sided exposure. 21 step density wedge, Stability ± 0.02 O.D., Repeatability ± 0.04 O.D. Capable of match calibration.

B. Densitometer:

Density range of 0.00 O.D. to 3.5 O.D. minimum, Reproducibility ± 0.01 O.D., Accuracy ± 0.02 O.D., Aperture: 2.5 mm, Reference density tablet, Self contained illumination, internally referenced.

C. **Thermometer:**

Digital, Temperature display in Celsius and/or Fahrenheit, Accuracy ± 0.9 °C (± 0.5 °F) over entire range, Temperature range 32.2°-37.8 °C (90°-100 °F), Resolution ± 0.05 °C (50.1 °F).

DOSIMETRY SYSTEM

Exposure meters are used in diagnostic radiology to evaluate the performance of imaging equipment and to assess levels of risk to both patients and operators associated with imaging procedures that involve exposure to x-ray. Some instruments may be unsuitable for acceptance tests due to lack of flexibility in both performance and positioning. There are some limited use instruments available that are suitable for QC tests, which have an ionization chamber permanently attached or contained within the casing. This type of unit may not be appropriate for exposures performed under automatic exposure control or automatic brightness control (fluoroscopy) since the ionization chambers are typically surrounded by attenuating electronics and lead shielding. Remote ion chamber connections are available on some units. The medical physicist will have to weigh the instrument's performance capabilities against its ease of use and make an informed decision based upon intended use. All results of these measurements should be interpreted, dated and signed by a medical physicist.

The required accuracy and precision of a given measurement will depend on the purpose for the measurement and the type of equipment being monitored. The report of Task Group No. 6 of the AAPM Diagnostic X-Ray Imaging Committee describes in detail the necessary performance characteristics of diagnostic exposure meters. The task group recommends that the combined uncertainties due to bias and random errors of in-beam exposure measurements not exceed $\pm 10\%$ of the true value. This is an overall accuracy requirement that must include uncertainties associated with precision, calibration, linearity, exposure rate dependence, and energy dependence.

The type of exposure measuring devices required at a given institution will vary depending on the range of equipment modalities in use. For all institutions however, a general purpose exposure meter and an area survey instrument will be essential.

A. General Purpose Meter:

Uses:

X-ray output, beam quality, exposure reproducibility, linearity, fluoroscopic entrance exposure rate, cine exposure/frame. Required for acceptance testing of radiographic, fluoroscopic, photofluorography, computerized radiography (CR), & DSA. May be used for routine QC on all except CT and Mammography.

Range:

17.4 μGy^* (2 mR) to 86.9 Gy (10 R) and from 173.8 $\mu\text{Gy}/\text{min}$ (20 mR/min) to 5.7 KGy/sec (1000 R/sec).

Precision:

<1 % standard deviation.

Calibration Accuracy:

Within $\pm 7.5\%$ of NIST standard at 3 points (1.5, 3.5, and 5 mm type 1100 Al HVL).

Linearity:

<0.5% or <0.43 μGy (0.05 mR) deviation from linearity for any exposure within the readout range of 17.4 μGy (2 mR) to 86.9 Gy (10 R), at a given exposure rate.

Energy Dependence:

<5% change from correction factor from 1.5 mm Al HVL to 10 mm Al HVL (1100 aluminum).

*1 mR = 0.258 x 10⁻⁶c Kg⁻¹ = 0.00869 mGy (Air Kerma)

Exposure Rate Dependence:

<1% change from calibrated response up to 261 Gy s⁻¹ (30 R s⁻¹) and <3% between 261 Gy s⁻¹ (30 R s⁻¹) and 695 Gy s⁻¹ (80 R s⁻¹).

Leakage:

<3.5 μGy (0.4 mR) in 30 s from 0.0 μGy and <0.5% in 30 s from 86.9 Gy (10 R) or max. reading (whichever is less). Must be correctable to within 0.1%.

Rate Meter:

<0.5% difference in rate mode versus integrate mode.

Amplification Gain (other than temperature and pressure):

Less than 0.5% change from calibrated reading after air gains are fully changed and reset.

B. Area Survey Meter:

Uses:

Environmental surveys of exposure and exposure rate within the procedure room. Meters are available with lower ranges (<1 μR) for environmental surveys of exposure and exposure rate outside procedure room barriers.

Range:

0.17 μGy (20 μR) to 8.7 Gy (1.0 R) and from 1.7 μGy hr⁻¹ (0.2 mR hr⁻¹) to 8.7 Gy hr⁻¹ (1 R hr⁻¹).

Precision:

<3% standard deviation.

Calibration Accuracy:

Within ± 20% of NIST standard at 2 points (3.5 and 10 mm type 1100 Al HVL).

Linearity:

<0.5% or <0.43 μGy (0.05 mR) deviation from linearity for any exposure within the readout range of 1.7 μGy (0.2 mR) to 8.7 Gy (1.0 R), at a given exposure rate.

Energy Dependence:

<30% change from correction factor from 0.35 mm Al HVL (>99.9% pure) to 10 mm Al HVL (type 1100).

Exposure Rate Dependence:

<5% change from calibrated response up to 8.7 Gy min^{-1} (1 R min^{-1}).

Leakage:

<3.5 μGy (0.4 mR) in 30 s from 0.0 μGy and <0.5% in 30 s from 86.9 Gy (10 R) or max. reading (whichever is less). Must be correctable to within 0.1%.

Rate Meter:

<2% difference in rate mode versus integrate mode.

Amplification Gain (other than temperature and pressure):

<0.5% change from calibrated reading after all gains are fully changed and reset.

C. High Sensitivity Meter:

Uses:

Image receptor input exposure and rate, and scatter and leakage radiation levels near (not in) the unattenuated useful beam. Required for acceptance testing on all except CT and mammography.

Range:

1.7 μGy (20 μR) to 8.7 Gy (1.0 R) and from 17.4 $\mu\text{Gy min}^{-1}$ (0.1 mR min^{-1}) to 869 Gy s^{-1} (100 R s^{-1}).

Precision:

<1% standard deviation.

Calibration Accuracy:

Within $\pm 7.5\%$ of NIST standard at 3 points (1.5; 3.5; and 5 mm type 1100 Al HVL).

Linearity:

<0.5% or <0.43 μGy (0.05 mR) deviation from linearity for any exposure within the readout range of 0.17 μGy (20 PR) to 8.7 Gy (1.0 R), at a given exposure rate.

Energy Dependence:

<5% change from correction factor from 1.5 mm Al HVL to 10 mm Al HVL (1100 aluminum).

Exposure Rate Dependence:

<1% change from calibrated response up to 26.1 Gy s^{-1} (3 Rs^{-1}) and <3% between 26.1 Gy s^{-1} and 69.5 Gy s^{-1} (8 Rs^{-1}).

Leakage:

<3.5 μGy (0.4 mR) in 30 s from 0.0 mGy and <0.5% in 30 s from 86.9 Gy (10 R) or max. reading (whichever is less). Must be correctable to within 0.1%.

Rate Meter:

<0.5% difference in rate mode versus integrate mode

Amplification Gain (other than temperature and pressure):

<0.5% change from calibrated reading after all gains are fully changed and reset.

D. **Mammography Meter:**

Uses:

X-ray output, beam quality, exposure reproducibility, linearity, and entrance skin exposure. Required for all mammography testing (QC and acceptance).

Range:

17.4 μGy (2 mR) to 86.9 Gy (10 R) and from 0.17 $\mu\text{Gy min}^{-1}$ (20 mR min^{-1}) to 86.9 KGy min^{-1} (1000 R min^{-1}).

Precision:

<1% standard deviation.

Calibration Accuracy:

Within $\pm 3.0\%$ of NIST standard at 3 points (0.25, 0.35, and 0.5 mm Al HVL, >99.9% pure aluminum).

Linearity:

<0.5% or <0.43 μGy (0.05 mR) deviation from linearity for any exposure within the readout range of 17.4 μGy (2 mR) to 86.9 Gy (10 R) at 8.7 Gy s^{-1} (1 R s^{-1}).

Energy Dependence:

<5% change from correction factor from 0.25 mm Al HVL to 1.0 mm Al HVL (>99.9% pure aluminum).

Exposure Rate Dependence:

<1% change from calibrated response up to 17.4 Gy s^{-1} (2 R s^{-1}).

Leakage:

<3.5 μGy (0.4 mR) in 30 s from 0.0 μGy and <0.5% in 30 s from 86.9 Gy (10 R) or max. reading (whichever is less). Must be correctable to within 0.1%.

Rate Meter:

<0.5% difference in rate mode versus integrate mode.

Amplification Gain (other than temperature and pressure):

<0.5% change from calibrated reading after all gains are fully changed and reset.

E. **CT Meter:**

Uses:

Beam quality, exposure reproducibility, linearity, mean scan axial dose, and CT dose index. Required for all CT testing (QC and acceptance).

Range:

5 $\mu\text{Gy}\cdot\text{m}$ (0.6 mR-m) to 5 Gy-m (575 R-m) and from 5 $\mu\text{Gy}\cdot\text{m s}^{-1}$ (0.6 mR-m s^{-1}) to 5 Gy-m s^{-1} (575 R-m s^{-1}).

Precision:

< 1% standard deviation.

Calibration Accuracy:

Within $\pm 7.5\%$ of NIST standard at 2 points (3.5, and 10 mm type 1100 Al HVL).

Linearity:

<0.5% deviation from linearity for any exposure within the readout range of 5 $\mu\text{Gy}\cdot\text{m}$ (0.6 mR-m) to 5 Gy-m (575 R-m), at a given exposure rate.

Energy Dependence:

<5% change from correction factor from 3.5 mm Al HVL to 10 mm Al HVL (1100 aluminum).

Exposure Rate Dependence:

<1% change from calibrated response up to
5 Gy-m s⁻¹ (575 R-m s⁻¹).

Leakage:

<0.1 μGy-m (0.01 mR-m) in 30 s from 0.0 μGy-m
and <0.5% in 30 s from 5 Gy-m (575 R-m) or max.
reading (whichever is less). Must be correctable to
within 0.1%.

Rate Meter:

<2% difference in rate mode versus integrate mode.

Amplification Gain (other than temperature and pressure):

<0.5% change from calibrated reading after all gains
are fully changed and reset.

Useful Features:

- A. Self-check of battery voltage, bias voltage, ion chamber/cable leakage, and hardware integrity.
- B. Automatic reset between exposures or remote control.
- C. Automatic temperature/pressure correction of display.
- D. Analog (bnc) radiation waveform output.
- E. RS-232 data port with fully programmable remote query capability (minimum 9600 Baud).

INVASIVE TEST EQUIPMENT

A. **High Voltage Divider/Measurement System:**

An invasive test device intended for the calibration and analysis of the x-ray generator. Connected between the x-ray generator and tube unit, it provides isolated low level analog voltage signals proportional to the applied kVp for measurement by external test equipment such as an oscilloscope or digital display device. Systems which also provide for the measurement of tube current, filament current, and exposure duration are preferred. The system should provide both analog

voltage outputs for display and measurement using and oscilloscope and, digital display of measured values.

Basic Specifications:

1. Capability for measurement of anode to cathode, anode to ground and cathode to ground kV.
2. Anode to cathode measurement range of 20 to 150 kV
3. Anode current range of 0.1 mA to 2 amps
4. Filament current range of 0 to 6 amps
5. Exposure time range of 1 ms to 8 s
6. kVp accuracy of $\pm 1\%$
7. mA accuracy of $\pm 2\%$
8. Filament current accuracy of $\pm 1\%$
9. Frequency compensation from 0 to 100 kHz
10. mAs range of 0.1 to 999 mAs with accuracy of $\pm 1\%$
11. Calibration traceable to NIST

B. High Voltage Cables, Insulation Oils and Insulation Greases:

High voltage cables, insulation oils and insulation greases are needed for the proper installation and use of a high voltage divider/measurement system. In general three types of cables are found in common use:

1. 3-conductor cable (for anode or cathode) used for most radiographic and fluoroscopic systems;
2. 4-conductor cathode cables and terminations for pulsed grid controlled or biased grid controlled applications; and
3. ALDEN type cables used on many mammographic systems.

The specific cable type required will depend on the given application. Of critical importance is that the cable length should be as short as possible in order to minimize the insertion impedance of the cable. The maximum recommended length is 1.5 m (5 ft.) and the cable should be equipped with straight termination. Cables should be rated for 75 kV to

ground for general use. Special connectors or adapters may also be required depending on the given application. The manufacturer of the x-ray equipment should be consulted when in doubt.

Insulation oils and grease are needed to provide proper electrical insulation of high voltage cable ends when inserted into cable end receptacles. In a given application always refer to and explicitly follow the recommendation of the x-ray system manufacturer.

C. mA/mAs Meter:

An mA/mAs meter is used for the invasive measurement of current flowing through an x-ray tube or for the measurement of the tube current-exposure time product. These devices may be “stand alone” intended for the measurement of mA/mAs, may be integrated as part of a high voltage divider-measurement system or may be an option provided on a digital multimeter. In use, the device is electrically connect in the ground return lead of the secondary of the x-ray generator transformer, frequently accomplished using test points provided within the generator. The majority of such devices provide digital display of the measured mAs and both battery and line operated devices are available. In the tube current mode typical ranges 0-20, 0-200 and 0-2000 mA having typical resolution of 0.01, 0.1 and 1 mA respectively should be provided. In the mAs mode typical ranges of U-200 and O-2000 mAs having resolution of 0.1 and 1, respectively should be provided. Accuracy of the device should be better than 2% of the reading for all ranges.

D. Digital Multimeter:

Digital multimeters are used for a wide variety of electrical measurements including DC voltage, AC voltage, DC current, AC current, resistance, frequency. temperature (by use of an external thermocouple) and may provide other features such as diode tests, continuity test, kV measurement and mAs measurement. Additionally, some meters provide true RMS voltage and current measurement for AC, peak sample and hold

capability and min - max capability. Choice of an appropriate digital multimeter(s) will depend on the specific application, and discussions with manufacturer's representatives will be necessary in the final selection. In general, a digital meter having a 3-1/2 digit display and basic DC accuracy <0.5% with the following measurement capabilities will be adequate:

Function	Range	# of Ranges
Vdc	1 V - 1000 V	4
Vac	1 V - 1000 V	4
Idc	20 mA- 10 A	4
Iac	20 mA- 10 A	4
Ω	1 k Ω - 1000 M Ω	6

High dc input impedance (10 M Ω and response time of less than 2 s) should be required.

STORAGE OSCILLOSCOPE

A. Basic Analog System Configuration:

1. Dual channel inputs
2. Storage capability
3. Channel 2 invertible
4. Scope camera
5. 1X/10X probes (2 each) with ground clips
6. Left, right, add, alt, & chop display modes

B. Specifications: Analog

1. Horizontal:
 - a. ≥ 2 MHz bandwidth (-3 db)
 - b. ≤ 100 $\mu\text{sec cm}^{-1}$ sweep rate
 - c. ≤ 5 nsec rise time
 - d. ≥ 1 MHz rep. rate in chop mode

2. Vertical:
 - a. 2 mV cm⁻¹ - 5 V cm⁻¹
 - b. ≤ ±2% Amplitude accuracy
 - c. ≤ 1 M Ω Input impedance

3. Trigger:
 - a. Line/Internal/External modes
 - b. Time delay
 - c. Normal/Auto/Single capture modes (either channel)

C. Environmental:

1. 0 - 50 °C operating temperature range
2. 100, 110, 120 V (AC) ±10% compatible
3. UL listed (UL 1244)

D. Additional System Requirements for Digital:

1. Range ≥ 20-50 MHz sampling rate
2. ≥ 8 bit Vertical resolution
3. ≥ 5 Wave form memories
4. Multi waveform display
5. Waveform smoothing optional
6. Serial interface for transfer of stored waveforms and required software

NON-INVASIVE TEST EQUIPMENT

A. **kVp Test Devices:**

Twenty to thirty years ago several devices were developed that allowed the non-invasive measurement of kVp by means of the exposure of a single film. The most recent of these devices, the Wisconsin kVp Test Cassette, exposes two strips of a film in a special single screen cassette for each kVp measurement. One strip is exposed through varying amounts of copper filtration and an adjacent strip is exposed through a uniform optical attenuator under the intensifying screen. The position of matching density is found between these two strips which then determines the kVp measurement.

Within the last fifteen years the kVp test cassette has been essentially replaced as a QC test tool by electronic kVp meters. Compared to the kVp test cassette, kVp meters provide better accuracy and much greater ease and rapidity of use: instead of taking about twenty minutes to provide a Kvp measurement, the kVp meters can provide an accurate measurement in seconds.

In its most basic form the kVp meter consists of a pair of matched, closely spaced detectors (diodes), filtered by different thicknesses of an attenuating material. The ratio of the signals from the diodes at any instant in time is a function of the x-ray tube potential (kV) at that time. Signal analysis methods within the kVp meter, sensitive to the peak x-ray tube potentials produced during the x-ray exposure, provide a direct measurement of the kVp. This digitally displayed kVp is usually some type of average of the relative peaks of the tube potential over the exposure time.

The signal from each detector can also be integrated over the exposure time and then the ratio of the integrated signals taken. This provides a different measure of tube potential, kV_{eff} , which is always lower than the kVp. Knowing the generator type (e.g., 3 phase - 12 pulse, 1 phase - full wave rectified), and thus the type of kV ripple, one can then apply a

reasonably accurate correction to the kV_{eff} measurement to produce an actual kVp (or kVp_{eff}) value derived from the kV_{eff} measurement. Typically kVp meters which supply such a measurement either make an internal determination of generator type or require the operator to select a switch indicating the generator type. The change from kV_{eff} to kVp_{eff} is then performed internally in the kVp meter.

Most kVp meters have an extended dynamic range provided by automatic gain control or logarithmic amplification in the initial signal processing stage. This feature provides a significant improvement in the ease of use: measurements can be easily obtained over a wide range of kVp, mA, and timer settings, with x-ray intensities from fluoroscopic to high kVp radiographic exposures. Some kVp meters are so limited in dynamic range that the distance used for the measurement and/or the exposure time must be changed each time the kV or mA setting is changed. These devices can be hard to use for routine QC measurements: they require careful selection of the time and distance for each kV and mA combination to be tested so that a valid kVp measurement is produced.

Another limitation of kVp meters is their frequency response to x-ray units employing high frequency generators. High frequency generators produce kV waveforms with frequencies up to 200 kHz. Most kVp meters have frequency responses with upper limits from 1 kHz to 10 kHz. Waveforms with significant ripple and with frequencies above the limit of the kVp meter will produce erroneously low kVp readings. However since the majority of high frequency units have fairly low ripple and are even advertised as “constant potential”, the errors introduced in the kVp measurement are generally not significant.

The time over which the kVp meter collects data for the kVp measurement does not necessarily correspond to the actual exposure time. With inexpensive kVp meters that are limited in dynamic range, the kVp measurement may frequently terminate significantly before the end of the exposure time.

Many kVp meters do not respond to the first 10 - 50 ms of the exposure while gain setting is being performed. In such a case variations in the early part of the kVp waveform may be missed in the normal operation of the kVp meter. For these meters it is helpful to have a mode in which the gain control can be frozen and measurements obtained from the beginning of the exposure.

Some kVp meters are rather sensitive to variations in positioning and tilting relative to the central ray and to the orientation of the detectors relative to the anode-cathode direction. They may also be quite sensitive to changes in the distance, collimation, and filtration. Other meters show less dependence on these parameters and can provide more accurate kVp readings with less concern regarding equipment setup.

Besides providing various measures of the kVp, certain models of kVp test devices also provide other useful QC test information such as: exposure time, exposure, exposure rate, relative mA and mAs, radiation waveforms, and kV waveforms. Some may be interfaced with computers to provide hard copy reports including waveforms without the use of an oscilloscope. While separate kVp meters are available for testing either conventional radiographic systems or mammographic systems, full range test devices with both capabilities are also available.

Basic Specifications:

1. kVp Range:
 - a. 50 - 150 kV for conventional diagnostic systems
 - b. 22 - 40 kV for mammographic systems (anode material and filter dependent)

2. kVp Accuracy:
 - a. 2-3% for conventional diagnostic systems
 - b. 1 kV for mammographic systems

3. kVp Resolution: 0.1 kV
4. kVp Reproducibility: 0.5%

Desirable Features:

Minimal dependence on variations in positioning, detector orientation, collimation, distance, filtration, with wide dynamic range capable of testing the clinical range of kVp and mA settings at exposure times as short as 50 ms.

B. X-ray Exposure Timers:

X-ray exposure timers are either available as single function devices or on kVp meters, exposure meters, or other multimeter systems. Many of these devices have threshold controls to vary the percent of peak at which the measurements begin and end. Some devices have the capability of counting pulses (from single phase equipment) as well as measuring exposure time in units of seconds and milliseconds.

Basic Specifications:

1. Range: 0.001 - 10 seconds (10,000 msec)
2. Accuracy: ± 1 pulse or ± 1 msec
3. Minimum Resolution: ± 1 pulse or ± 0.1 msec
4. Threshold Adjustment: 0 - 90%
5. Display: 3 1/2 digits

FOCAL SPOT EVALUATION TEST TOOLS

A. Star Patterns:

0.5°, 1.0°, 1.5°, 2.0°: Lead foil screens 0.03 mm thick between plastic plates; Pattern angles - 0.5° and 1.0° for mammography/microfocus tubes, 1.5° and 2.0° for conventional tubes.

- B. **Slit Camera:**
Slit width of 10 μm ($\pm 1 \mu\text{m}$) with 4° relief angles on each jaw, Slit length of 10mm.
- C. **Pinhole Camera:**
Still available but are not recommended at this time as the NEMA standard.
- D. **Resolution Bar Patterns:**
Sector (0.4°) or group test patterns. Perpendicular bar groups recommended for image evaluation of image intensifiers and video systems. Resolution range depends on the specific application. Resolution ranges available from 1 - 20 LP/mm.
- E. **Alignment Stand:**
Multipurpose focal spot stand, Adjustable height. Fluorescent screen base with centering marks.
- F. **Power Magnifier with Graticule:**
10-20 power magnifier.

NOTE: All of the above are not necessary for routine testing. See NEMA standards for recommended methods.

CONVENTIONAL TOMOGRAPHY TEST TOOLS

- A. **Pinhole:**
For stability, the pinhole should be 3.2 to 4.8 mm (1/8 to 3/16 inch) diameter in 3.2 mm (1/8 inch) (min) stainless steel plate or a laminated 1.6 mm (1/16 inch) lead plate.
- B. **Resolution:**
The resolution object should consist of wire mesh strips in four steps ranging from 0.8 to 2.0 holes mm-1 (16 to 40 mesh) cast in acrylic with a 10 - 15 degree angle to the horizontal surface.

C. Slice Thickness/Cut Level:

This test object should consist of a step-wedge with twelve steps, at millimeter increments in height, starting at 1 mm above the base. Each step must be uniquely identified with radio-opaque markers.

D. Accessories:

The phantom should be supplied with a supporting device to elevate it above the table top by 5 - 15 cm and several aluminum (exact alloy is not critical) or acrylic attenuators, each at least 2 cm thick.

PHANTOMS OR ATTENUATING MATERIALS

A. Attenuating Materials:

1. Aluminum Filters:

For HVL determination of x-ray generators operating at kVp values of < 140 kVp. Thicknesses ranging from 0.5 mm to 2.0 mm for a total thickness of 10 mm. (0.1 to 1.0 mm for mammography). Type 1100 aluminum or higher purity may be used.

2. Copper Sheets:

For HVL determination of x-ray generators operating at kVp values of 140 - 400 kVp. Thicknesses ranging from 0.1 mm to 1.0 mm.

3. Lead Sheets:

For use in measuring maximum fluoroscopic output in automatic brightness controlled mode of operation. Minimum of 3.2 mm (1/8 inch) thick.

4. Acrylic or Tissue-Equivalent BR-12 Material:

For use in evaluating mammography automatic exposure control (AEC) system operation. Thicknesses ranging from 0.5 cm to 2.0 cm, 9 cm X 12 cm minimum size, total thickness of 8 cm.

5. Acrylic:
For use in evaluating radiographic automatic exposure control (AEC) system operation. Thicknesses range from 2.5 cm to 25 cm, 35.6 cm x 35.6 cm minimum size.

B. Phantoms:

1. CT Phantoms for QC and Dosimetry:
 - a. Quality Control:
As provided by manufacturer.
 - b. Dosimetry:
The head dosimetry phantom consists of a 16 cm diameter clear acrylic cylinder 1.5 cm in length. The body dosimetry phantom consists of a 32 cm diameter clear acrylic cylinder 15 cm in length. Both phantoms have 8 surface dosimeter holes and one central dosimeter hole with removable acrylic rods or alignment rods. The exact configuration of the phantoms is given in 21 Code of Federal Regulations 1020.33.
2. Mammography Phantom:
The phantom currently used in the American College of Radiology Mammography Accreditation Program is a clear acrylic phantom that is equivalent to a 4.2 cm compressed breast (50% adipose, 50% glandular) for film-screen mammography and a 4.5 cm compressed breast for xeromammography. Test objects, embedded in a wax matrix, include simulated micro-calcification (specks), soft tissue fibrils (nylon fibrils), and spherical tumor-simulating masses.

C. **Clinical Attenuation Phantoms (AAPM Report No. 31):**

1. **Modified ANSI Phantoms:**

a. **Abdomen/Lumbar Spine:**

This phantom consists of seven (7) 30.5 x 30.5 x 2.54 cm pieces of clear acrylic for a total thickness of 17.78 cm thick (Figure 1). The phantom has been modified to include a 7.0 x 30.5 cm piece of aluminum (type 1100 alloy) 4.5 mm thick in order to provide additional attenuation in the spinal region.

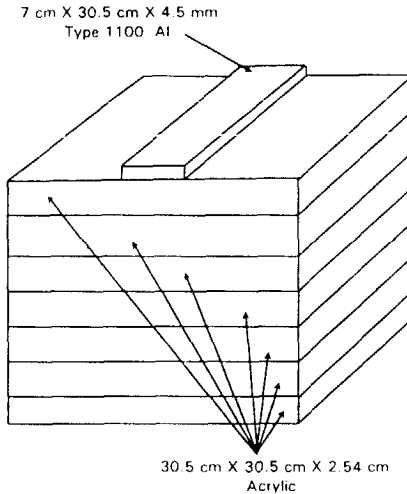


Figure 1.

b. Skull:

This phantom consists of four (4) 30.5 x 30.5 x 2.54 cm pieces of clear acrylic, one (1) 30.5 cm x 30.5 cm x 1.0 mm sheet of aluminum (type 1100 alloy), one (1) 30.5 cm x 30.5 cm x 2.0 mm sheet of aluminum (type 1100 alloy), and one (1) 30.5 x 30.5 x 5.08 cm piece of acrylic (Figure 2).

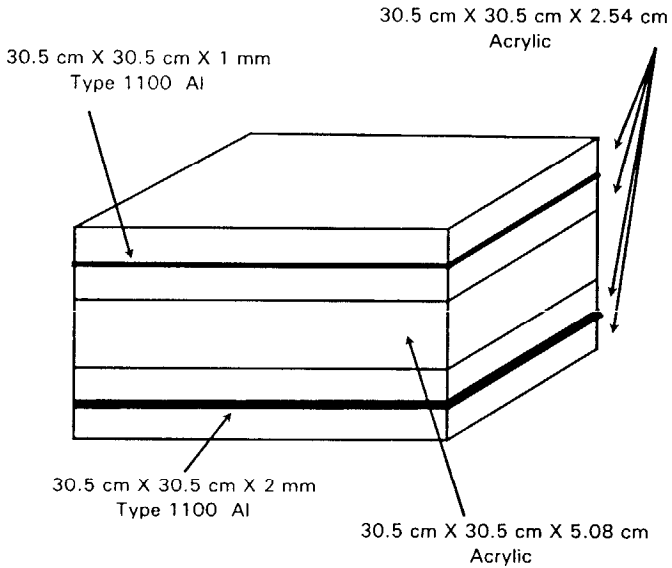


Figure 2.

c. Extremity:

This phantom consists of one (1) 30.5 cm x 30.5 cm x 2.0 mm thick sheet of aluminum (type 1100 alloy) sandwiched between two (2) 30.5 x 30.5 x 2.54 cm thick pieces of clear acrylic (Figure 3).

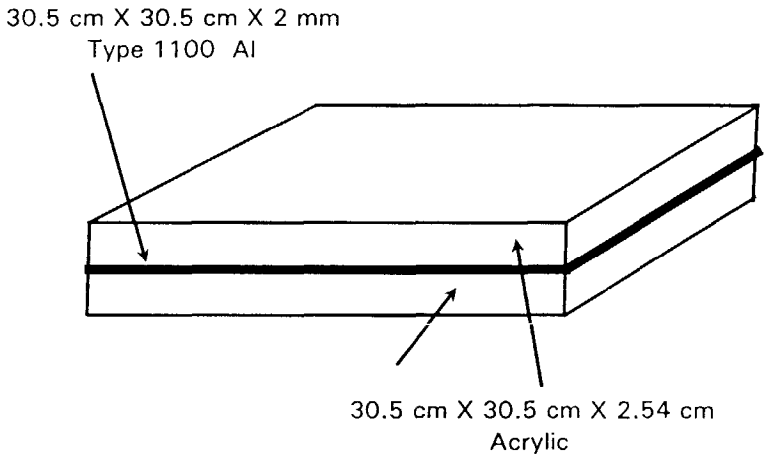


Figure 3.

d. Chest:

This phantom consists of four (4) 30.5 x 30.5 x 2.54 cm pieces of clear acrylic, one (1) 30.5 cm x 30.5 cm x 1.0 mm sheet of aluminum (type 1100 alloy), one (1) 30.5 cm x 30.5 cm x 2.0 mm sheet of (type 1100 alloy) aluminum, and a 5.08 cm air gap (Figure 4).

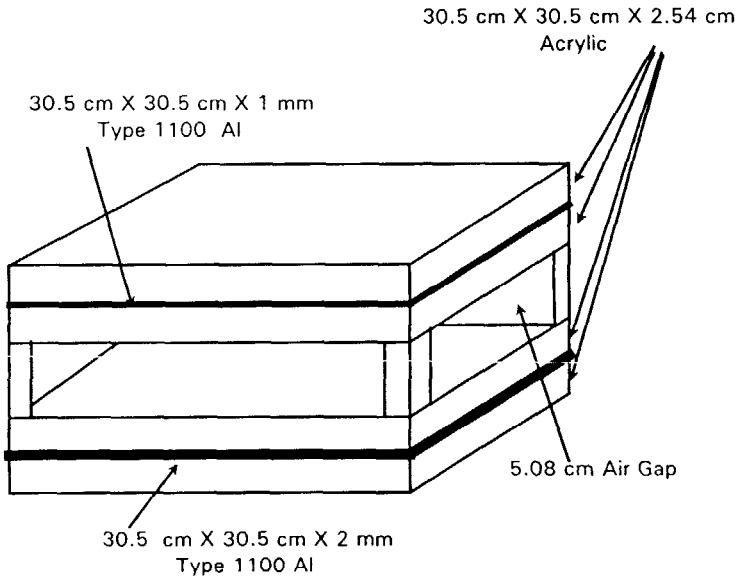


Figure 4.

2. CDRH LucAl Phantoms:

a. CDRH LucAl Chest:

This phantom consists of two (2) 25.4 x 25.4 x 0.95 cm pieces of clear acrylic, one (1) 25.4 x 25.4 x 5.4 cm piece of clear acrylic, one (1) 25.4 cm x 25.4 cm x 0.25 mm sheet of aluminum (type 1100 alloy), one (1) 25.4 cm x 25.4 cm x 0.16 mm sheet of aluminum (type 1100 alloy), and a 19 cm air gap (Figure 5).

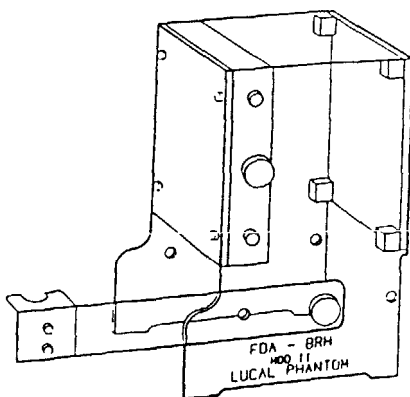


Figure 5.

- b. CDRH LucAl Abdomen/Lumbar Spine:
This phantom consists of 25.4 x 25.4 cm pieces of clear acrylic totaling 16.95 cm thick in the soft tissue region and one (1) 6.99 x 25.4 x 0.46 cm strip of aluminum (type 1100 alloy) and 18.95 cm total clear acrylic thickness for the spinal region (Figure 6).

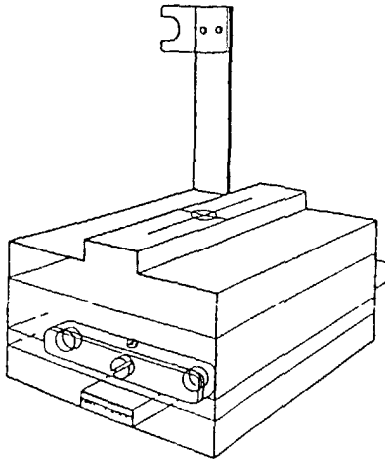


Figure 6.

c. CDRH LucAl Fluoroscopy:

This phantom consists of 17.8 x 17.8 cm pieces of clear acrylic totaling 19.3 cm thick and one (1) 17.8 x 17.8 x 0.46 cm sheet of aluminum (type 1100 alloy) (Figure 7).

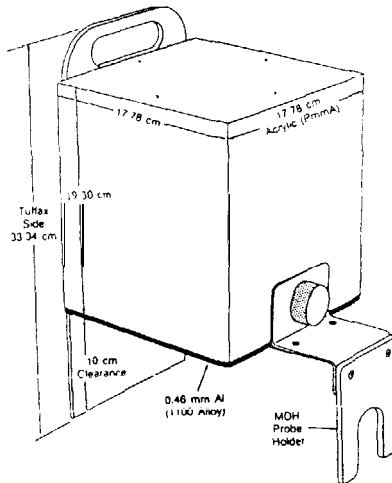


Figure 7.

3. DSA Phantoms:
Typical phantoms are described in AAPM Report No. 15.

LEEDS TEST OBJECTS

The LEEDS test objects are a comprehensive collection of test objects/patterns which may be used to assess the performance of a wide variety of x-ray imaging systems. These test objects are available for radiographic, fluoroscopic, digital and mammographic imaging systems.

FLUOROSCOPIC EVALUATION TEST TOOLS

A. **High Contrast Resolution Mesh:**

Used for the evaluation of the resolution of fluoroscopic imaging systems. Plastic plates containing 8 groups of wire mesh screening. The wire mesh screening should be made of copper or brass in mesh sizes ranging from 9 to 23 lines/cm (16 to 60 lines/inch) for conventional fluoroscopic units and from 12 to 39 lines/cm (30 to 100 lines/inch) for evaluation of cinefluoroscopy units.

B. **Fluoroscopic Threshold Contrast Test Tool:**

Used to provide a quantitative evaluation of fluoroscopic threshold contrast. Consists of two 15 cm x 15 cm x 6.3 mm (6" x 6" x 1/4") thick aluminum plates. Each plate contains an array of 1.1 cm targets of varying contrast arranged in three columns. Three 15 cm x 15 cm x 1 mm (6" x 6" x 1 mm) copper attenuation sheets are also needed. Tables of target contrast versus kVp permit determination of target contrast at the tested fluoroscopic kVp values.

C. **Centering and Alignment Tool:**

Used to determine the perpendicularity of the central ray of the x-ray beam. The device should be a box or cylinder whose sides are perpendicular with its bottom to within 1 degree with a centrally located vertical wire or pair of BBs (one on the top surface, one on the bottom) works well. It should be noted that this device can be used for radiographic units as well as fluoroscopic units. In addition, a bubble level is essential to confirm tube level, table or film level, and phantom level.

- D. **Beam Restriction and Sizing Evaluation Device:**
An aluminum plate with four sliding brass strips dividing the plate into quarters. Holes, at 12.7 mm (1/2 inch) intervals, should be drilled in perpendicular lines beneath the sliding brass strips. Recommended minimum size of 23 x 23 cm (9 x 9 inches).

RADIOGRAPHIC X-RAY AND LIGHT FIELD EVALUATION TEST TOOLS

- A. **Collimator Alignment Tool:**
The collimator test tool should be capable of recording the position of the light field with radio-opaque markers for field sizes ranging from 15 to 36 cm (6 to 14 inches). Opaque markers should also visually verify agreement to within ± 2 cm (± 0.8 inches), to mark the location of the light field cross-hair shadow, and to record the orientation of the film. A variety of simple tools are available. A home-made device consists simply of placing two pennies tangent to each border (one inside, one outside) with one additional penny to mark the center and one off center for orientation.
- B. **Fluorescent Screen Strips:**
Minimum length of 50 cm (20 in) to allow evaluation of largest x-ray field size. Note: It does not give a permanent record.

SCREEN/FILM CONTACT

Radiographic and Mammographic Wire Mesh:

- A. **Radiographic:**
1.6 - 3.1 lines/cm (4 - 8 lines/inch) mesh made with 16 - 20 gauge brass wire encased in acrylic, 36 x 43 cm (14 x 17 inches), total thickness should not exceed 3 mm (1/8 inch).

B. Mammographic:

40 mesh brass screen encased in acrylic, 24 x 30 cm, total thickness should not exceed 3 mm (1/8 inch).

GRID ALIGNMENT

Grid Alignment Test Tool:

- A. Lead plate with five to seven 9.5 mm (3/8 inch) holes on a line on 2.54 cm (1 inch) centers sandwiched between Formica. Lead thickness of 1.6 mm (1/16 inch). Dimensions of 9 x 23 cm (3.5 x 9 inches).
- B. Two lead plate covers sandwiched in Formica. Dimensions of 6 x 9 cm (2.5 x 3.5 inches).

VIDEO SYSTEM EQUIPMENT

A. Multisync Video Monitor:

A multisync, monochrome, composite input video monitor is frequently useful in the analysis and trouble shooting of modern, video based medical imaging systems. The increasing use of video based imaging systems which employ nonstandard vertical line rules and horizontal scanning frequencies necessitates that a multisync video monitor be available for use with other video test equipment. The basic desirable characteristics for such a monitor are as follows:

- | | |
|---|-----------------------------|
| 1. Diagonal size | 22.9 cm (9 inch)
minimum |
| 2. Vertical line rate range | 525 - 1250 |
| 3. Horizontal scanning
frequency range | 15.5 kHz - 36 kHz |
| 4. Aspect ratio capability | 4:3 to 1: 1 adjustable |
| 5. Resolution | 1000 line |
| 6. Video input level | up to 2 Volts p-p |
| 7. Brightness | 50 ftL minimum (171 nit) |

B. Video Level Meter:

A video level meter is a precision test instrument which may be used for the measurement of video levels during the set up, optimization and performance assessment of video based medical imaging systems and their components. It is used in place of an oscilloscope and provides a direct digital readout of the video level within the sampled portion of the video image.

The video signal to be measured/analyzed is connected to the input of the video level meter. Within the meter a video marker signal in the form of a sampling window whose height, width and location within the image may be adjusted is combined with the incoming video signal. The combined signal is then output to a small display monitor to provide visual location of the sampling window within the image. The average value of the video level within the window is measured and displayed. The frequency response of the device is designed around broadcast video and therefore must be inserted following the primary image display and used with a separate monitor to visualize sampling location.

Specifications for the video level meter are as follows:

1. Input:
Video or composite video, sync negative; 75 ohm
2. Output:
Incoming video signal superimposed with marker pulse, 75 ohm
3. Vertical line selection:
Thumb wheel control
4. Window height:
Potentiometer adjustable
5. Window width:
Potentiometer adjustable

6. Horizontal window location:
Potentiometer adjustable delay
7. Video level:
Digital display in mV referred to blanking
8. Range:
-600 to +1400 mV
9. Sampling pulse:
 - a. Line 1 to line N vertically
 - b. 1 to 64 μ sec from leading edge of sync pulse
horizontal
 - c. 1 to 50 lines height
 - d. 0.3 to 5 μ sec width

C. Pincushion Distortion Grid:

A 1 cm grid for measuring pincushion distortion or evaluation of the size of the field of view.

D. Rotating Spoke Test Object:

The rotatable spoke test pattern consists of six, 13 cm (5") long steel wires having diameters of 0.559 mm (0.022"), 0.432 mm (0.017"), 0.330 mm (0.013"), 0.254 mm (0.010"), 0.178 mm (0.007"), and 0.127 mm (0.005") arranged at 30 degree intervals sandwiched between two circular pieces of 0.32 cm (1/8") thick acrylic. The test pattern is mounted on a synchronous motor which rotates at a speed of 30 rpm. The spoke test pattern is used in conjunction with a variable thickness, uniform attenuator of either water or acrylic to drive the automatic brightness control (ABC) fluoroscopic system to normal clinical ranges. Limiting spatial resolution can be assessed with the disk stationary. When the disk is rotating the linear velocity of any spoke is dependent upon the radius from the center of the disk and provides an overall assessment of image quality including the influence of contrast, noise and motion. The linear velocity of the spoke at its maximum radius approximates the speed of the heart wall during systole. The 0.330 mm (0.013") wire approximates the 0.356 mm

(0.014”) guide wire commonly used during percutaneous transluminal coronary angioplasty (PTCA) studies. Note: This is used for cardiology/angiography units to determine lag and motion blur.

COMPUTER SYSTEMS (HARDWARE AND SOFTWARE)

A. Office PC Equivalent System: Hardware Selection

1. Apple Macintosh, IBM and IBM Compatible Platform:

There are several models of systems available with different video display systems built-in. It is recommended that models with high processing capabilities and high operating frequencies be used. Be aware that, as software applications evolve hardware requirements have increased and your system should be up gradeable.

The monitor size varies and should be large enough for minimal eye strain. In general, a 36 to 38 cm (14” to 15”) monitor is considered satisfactory.

2. Laptop Personal Computer:

It is often desirable to conduct testing of radiological imaging equipment with various commercial products under the direct control of a micro computer. It is then desirable to have a laptop in addition to a desktop type. Often the laptop is available as an option to such measurement devices as non-invasive kVp measurement devices, an automatic film processing quality assurance kit, and as a service tool to function as the communication terminal to the imaging system. The laptop systems are just as

powerful as many desktop systems today, and it is possible to employ a laptop to function as a desktop.

Whether using laptop or desktop, the hardware selection should be based on application software. Be aware that as software applications evolve hardware requirements have increased.

B. Software Recommendations:

The following software programs may be useful in the operation of a typical medical physics program:

1. Word Processors
2. Spread Sheet Program
3. Data Base Management Program
4. Graphics/Drawing Program
5. Forms Generation, Fill, and File program
6. Communications Program
7. Presentation/Graphics Program
8. Desktop Publishing Program
9. Screen/Printer Font Generation Management Program
10. Mathematics, Graphs, Data Base Management Program

C. Printer:

A letter quality text printer with a high resolution graphics capability is desired.

MULTI-FORMAT CAMERAS

A. Video Test Pattern Generator:

A video test pattern generator is used for the adjustment and optimization of medical imaging display devices and hard copy recording cameras. In general, only monochrome test pattern generators are required in medical imaging. Available test pattern generators vary widely in capability and individual applications will, to some extent, dictate video pattern generator requirements. In order to properly assess and optimize the performance of a medical imaging display or

recording device the video test pattern generator must provide a pattern of patterns which allow the assessment of high and low contrast resolution, gray scale performance, brightness uniformity and geometric distortion. This may be accomplished by multiple patterns containing the individual elements. An accepted combined pattern for monochrome medical imaging display and recording devices has been developed and specified by the Society of Motion Picture and Television Engineers (SMPTE). A video pattern generator capable of producing this specific pattern will be found adequate for the majority of all applications involving medical imaging display and recording devices. If a SMPTE pattern generator is used it should be capable of generating the pattern for those line rates and aspect ratios likely to be encountered. This may be accomplished in a single pattern generator or may require line rate and aspect ratio specific pattern generators. For more extensive evaluation of medical imaging display and recording devices a video generator capable of a wide range of patterns at multiple line rates and aspect ratios should be considered. Some recording devices may already contain the SMPTE pattern in their software.

B. Video Test Pattern Tape:

Video test pattern tapes are available in VHS, S-VHS and U-Matic format and are intended for use in the periodic quality control of medical imaging devices used in systems which incorporate video tape recorders. Two types are generally available. The first is intended to validate the overall electrical and mechanical performance of the video tape player and will demonstrate problems associated with head alignment, frequency response, etc. The second type of tape is a high quality recording of the SMPTE test pattern and is intended for use in establishing and assessing the performance of the video display device. When used in conjunction with a video test pattern generator it is possible to isolate video cassette record and play problems from display device problems.

MISCELLANEOUS

- A. Aluminum step wedge
- B. Acrylic step wedge
- C. Small lead numbers
- D. Direct exposure film holders
- E. Six to ten power monocular with stand for checking image intensifier focus
- F. Ring stand and clamps
- G. Torpedo level
- H. Long nose pliers
- I. Wrench
- J. Diagonal cutter/pliers
- K. Allen hex wrenches
- L. Plastic ties
- M. Small parts tool kit
- N. Philips and regular screw drivers
- O. Barometer
- P. Inch/millimeter ruler
- Q. Radio-opaque ruler
- R. Protractor
- S. Caliper
- T. Ultraviolet lamp: a UL-listed ultraviolet lamp assembly with a longwave uv filter. Device should be hand held.

BIBLIOGRAPHY

- AAPM Report No. 12. "Evaluation of Radiation Exposure Levels in Cine Cardiac Catheterization Laboratories." AAPM Cine Task Force of the Diagnostic Radiology Committee, 1984.
- AAPM Report No. 14. "Performance Specifications and Acceptance Testing for X-Ray Generators." Automatic Exposure Control Devices and Diagnostic X-Ray Imaging/X-Ray Generators and Automatic Exposure Control (AEC) Devices Task Group, 1985.
- AAPM Report No. 15. "Performance Evaluation and Quality Assurance in Digital Subtraction Angiography." Diagnostic X-Ray Imaging Committee/Digital Radiography/Fluorography Task Group, 1985.
- AAPM Report No. 25. "Protocols for the Radiation Safety Surveys of Diagnostic Radiological Equipment." Diagnostic X-Ray Imaging Committee Task Group #1, 1988.
- AAPM Report No. 29. "Equipment Requirement and Quality Control for Mammography." Diagnostic X-Ray Imaging Committee Task Group #7, 1990.
- AAPM Report No. 31. "Standardized Methods for Measuring Diagnostic X-Ray Exposures." Diagnostic X-Ray Imaging Committee Task Group #8, 1990.
- Barnes, G. T. and G. D. Frey, eds.. Screen Film Mammography (proceedings of the SEAAPM Spring Symposium, April 6, 1990). Medical Physics Publishing, 1991.
- Burkhart, Roger L.. Diagnostic Radiology Quality Assurance Catalog, HEW #78-8028, 1977.
- Burkhart, Roger L., Diagnostic Radiology Quality Assurance Catalog (Supplement), HEW #78-8043, 1978.
- Burkhart, Roger L., Checklist for Establishing a Diagnostic Radiology Quality Assurance Program, HEW #83-8219, 1983.
- Cacak, R. K., P. L. Carson, G. Dubuque, J. E. Gray, A. G. Haus, W. R. Hendee, and R. P. Rossi. Application of Optical Instrumentation in Medicine V (proceedings of the SPIE Seminar, September 16-19, 1976: Volume 96).
- Conway, B. J. et al. Beam Quality Independent Attenuation Phantom for Estimating Patient Exposure from X-Ray Automatic Exposure Controlled Chest Examinations, Med Phys 11(6), Nov/Dec 1984.

- Conway, B. J. et al., Patient-Equivalent Attenuation Phantom for Estimating Patient Exposures from Automatic Exposure Controlled X-Ray Examination of the Abdomen and Lumbo-Sacral Spine, *Med Phys.* 17(3), May/June 1990.
- CRCPD Suggested State Regulations.
- Goldman, L. W. and S. Beech, Analysis of Retakes: Understanding HEW # 79-8097, 1979.
- Gray, Joel E., *Photographic Quality Assurance in Diagnostic Radiology, Nuclear Medicine, and Radiation Therapy, Volume I: The Basic Principles of Daily Photographic Quality Assurance*, HEW #76-8043, 1976.
- Gray, Joel E., *Photographic Quality Assurance in Diagnostic Radiology, Nuclear Medicine, and Radiation Therapy, Volume II: Photographic Processing, Quality Assurance, and the Evaluation of Photographic Materials*, HEW #77-8018, 1977.
- Gray, Joel E., N. T. Winkler, J. Stears, and E. D. Frank, *Quality Control in Diagnostic Imaging*, University Park Press, 1983.
- Hendee, William R., *The Physical Principles of Computed Tomography*, Little, Brown, 1983.
- Hendee, William R. (ed.), *The Selection and Performance of Radiologic Equipment*, Williams and Wilkins, 1985.
- Hendee, W. R. and R. P. Rossi, *Quality Assurance for Radiographic X-Ray Units and Associated Equipment*, HEW # 79-8094, 1979.
- Hendee, W. R. and R. P. Rossi, *Quality Assurance for Fluoroscopic X-Ray Units and Associated Equipment*, HEW # 80-8095, 1979.
- Hendee, W. R. and R. P. Rossi, *Quality Assurance for Fluoroscopic X-Ray Units and Associated Equipment*, HEW # 80-8095, 1979.
- Hendee, W. R. and R. P. Rossi, *Quality Assurance for Conventional Tomographic X-Ray Units*, HEW # 80-8096, 1979.
- Hendee, William R., Edward L. Chaney, and Raymond P. Rossi, *Radiologic Physics, Equipment, and Quality Control*, Yearbook Medical Publishers, 1977.
- Hendrick, Edward R. et al., 1990 Mammography Quality Control manuals, American College of Radiology and the American Cancer Society. JCAHO Accreditation Standards.
- Lin, P. P., R. J. Kriz, K. J. Strauss, P. L. Rauch, and R. P. Rossi, eds. *Proceedings of the AAPM/ACR/SRE Symposium of October 1 and 2, 1981*, AIP 1982.

- McLemore, Joy C., Quality Assurance in Diagnostic Radiology, Yearbook Medical Publishers, 1981.
- Rothenberg, L. N., et al, Mammography--A User's Guide, NCRP Report No. 85, 1986.
- Seibert, J. A., G. T. Barnes, and R. Gould, eds. Specification, Acceptance Testing, and Quality Control of Diagnostic X-Ray Imaging Equipment (Proceedings of the 1991 AAPM Summer School).
- Waggener, R. G., and C. R. Wilson, eds., Quality Assurance in Diagnostic Radiology (AAPM Monograph No. 4), AIP 1980.
- Wagner, A. J., G. T. Barnes, and X. Wu, Assessing fluoroscopic contrast resolution: A practical and quantitative test tool, Med. Phys. 18, 894-899 (1991).
- Wagner, L. K., et al.. Recommendations on performance characteristics of diagnostic exposure meters (The report of Task Group No. 6 of the AAPM Diagnostic X-Ray imaging Committee), Medical Physics vol. 19, No. 1, Jan/Feb 1992, p.p. 231 - 241.