PERFORMANCE EVALUATION
OF
HYPERTHERMIA EQUIPMENT

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PERFORMANCE EVALUATION OF HYPERTHERMIA EQUIPMENT †

REPORT OF
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'AAPM Report No. 27 covers hyperthermia treatment planning.

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I.RATIONALE

For hyperthermia to reach the status of an accepted modality[41] unequivocal proof that it is effective must be obtained. A clear, causal relationship must be demonstrated between the application of the modality and the response of the disease. A thorough understanding of the equipment is required to demonstrate such a relationship. Further, to maximize the possibility that patients treated with the equipment receive the desired effect, the equipment should conform to certain minimum standards. Equipment for hyperthermia should heat human tissue in a controlled, safe, and reproducible fashion. All ancillary equipment should operate as intended, without serious risk of failure or injury to the patient or operator. Several parameters which indicate the effect of the treatment should be monitored with suitable accuracy.

This document has been prepared as a guide to assessing the performance of hyperthermia equipment. The procedures described are felt to constitute the minimum necessary for adequate evaluation of each piece of equipment. These recommendations may be utilized for developing purchase specifications; should be considered for acceptance testing of new equipment; and should be incorporated into a quality assurance program. Performance criteria expressed here are considered the minimum acceptable for a clinical system.

As is true of many newly-introduced modalities, hyperthermia equipment and procedures undergo frequent modification. Revisions of this document will be prepared when necessary.

II.INTRODUCTION

Most clinical hyperthermia systems operate by causing a target volume of tissue to be exposed to electromagnetic (EM) fields or ultrasound (US) radiation. The EM or US power is supplied by a generator and delivered to the patient through an applicator. A diagram of the fundamental components of a hyperthermia system is shown in Figure 1. Applicators in use today consist of implantable or external electrodes, antennas, waveguides, and transducers. These devices may deposit energy to only a small volume of tissue directly adjacent to the heating device, or they may be intended to deliver regional or whole-body hyperthermia.
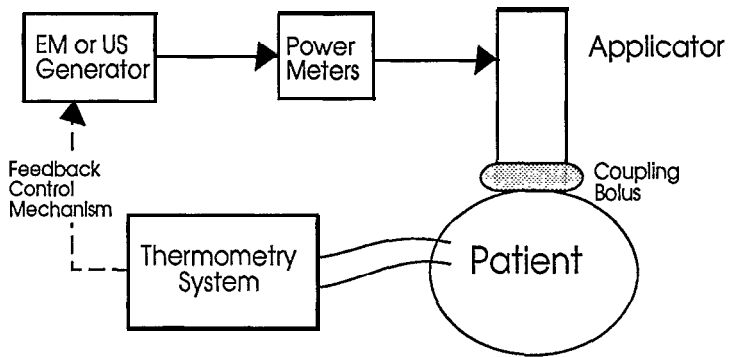
Figure 1: The fundamental elements of a representative hyperthermia system.

The clinical outcome of hyperthermia depends critically on the tissue temperatures obtained during the procedure.[42,43,45,46,50,53] It is therefore important to have accurate information concerning the temperature throughout the treated region of the patient. Although non-invasive thermometry which could yield complete 3-dimensional temperature information would be most desirable, such equipment is not presently available. In the absence of such an ideal thermometer, clinicians use small implanted probes, and in some cases move the probes within implanted catheters to obtain one-dimensional temperature profiles.[22] To minimize the need for mechanical mapping, probes having multiple temperature sensors distributed along their length often are used.

Clinical experience has shown that only a relatively small number of temperature probes can be inserted into a patient. Consequently, the information concerning temperature distributions within the treated region will be incomplete. The problem is especially pronounced in situations where large temperature gradients are encountered: tissue temperature variations exceeding 1°C per mm have been observed.[42] Thus, the clinician has no assurance that the temperature throughout the tumor will be represented adequately by that measured at a few points.

The temperature distribution obtained during hyperthermia treatment is influenced by the power deposition pattern and by the thermal and physiological properties of the tissue under treatment. The tissue properties vary from one anatomical site to another and from patient to patient. The idealized power deposition pattern can be characterized in the laboratory using a phantom model which is tissue-equivalent at the frequency of EM or US radiation being used. Power deposition is quantified in Watts/ kg, and is described as the Specific Absorption Rate (SAR).[23] To assure proper performance of an applicator, the SAR pattern should be evaluated under controlled laboratory conditions not only prior to its first clinical use but also at regular intervals as part of a clinical quality assurance program. During routine use, a deterioration of applicator performance could be indicated by a sudden change in the power required to achieve the desired temperature. The operator should be continually on the alert for such changes.

The temperature to which the tissue is raised depends upon, among other things, the amount of EM or US power absorbed by the tissue. This quantity is determined by the power supplied by the generator, and adjustment of the gen-

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erator is most often the method by which tissue temperatures are controlled.

A variety of physiological changes, including blood flow and pH, have been reported following hyperthermia.[54] In addition, many investigators have observed that their patients appear to change in some physiological manner during the course of treatment, so that the amount of power required at one heating session may be different from the level required at previous or succeeding sessions. The variation from one day to the next may be an indication of a response to the therapy, and may therefore be an important quantity to document. Documentation might be achieved through the relationship between desired temperature and the power required to reach that temperature. Consequently, a reasonably accurate indication of the power delivered during the treatment is required.

Some of the procedures described here are necessarily complex, and require the use and understanding of sophisticated equipment. It is therefore recommended that the procedures be performed or supervised by an individual with training and experience in clinical hyperthermia physics and engineering. A minimal background might consist of academic and practical training in medical physics or clinical engineering, followed by attendance at a formal course in hyperthermia physics. As with other forms of medical treatment, a dedication to the task is mandatory.

An exhaustive analysis of a hyperthermia system may exceed the capabilities of most clinical departments. Manufacturers of hyperthermia equipment should provide representative data describing the performance of their equipment, and recommended operating parameters. Suitable phantoms should be included with each system. The user of the equipment is encouraged to follow the procedures outlined below to verify compliance of the equipment with the manufacturer's specifications.

III. PERFORMANCE EVALUATION PROCEDURES

A.   Visual Inspection

Some important characteristics of operation may be determined from a visual inspection of the system. Devices such as indicator lamps, digital displays, and meters should be energized to ensure that they are functional. Electrical cables should be inspected for wear or breakage, and for exposed terminals. Loose connections should be tightened. Implantable antennas which exhibit bends, fraying or other

damage that could affect performance should be discarded. Other devices which come in contact with the patient should be inspected to verify the integrity of insulation and protective coatings, and the absence of abrasive surfaces. Temperature probes should be examined for bends, breaks, or damage to connectors or insulation, and for the exact location of the temperature sensor(s). With opaque probes, moving the probe across a steep thermal gradient may be required to locate the position of the sensor.

   B.   Thermometry Equipment

    The choice of a particular thermometry system should be made following careful consideration of its intended application. Any measuring instrument can be considered acceptable for a given purpose if the error contributed by the instrument is small compared to other errors or uncertainties in the measurement. Hence, in local hyperthermia where large temperature fluctuations are encountered, an extremely accurate thermometer may not be required. An overall error not exceeding 0.3°C is probably acceptable, but achieving this accuracy in a clinical environment may require that the thermometer agree with an institution's standard to within 0.1 or 0.2%. In whole body hyperthermia, on the other hand, where temperatures are only a few tenths of one degree below the lethal limit and homogeneity is excellent, instrument errors of more than +/-0.05% may be unacceptable.

   1.   Calibration Procedure

        The accuracy of the thermometry system should be verified by comparing its readings to a thermometer having its calibration traceable to the National Bureau of Standards (NBS). A high-quality mercury-in-glass thermometer with a precision of 0.05°C makes a practical, reliable and affordable standard. This standard should be calibrated to the NBS standard at two or more points within the treatment range, e.g. at 41°C and at 45°C. To carry out the comparison, the temperature probe should be affixed to the standard, so that the sensing element is close to the mercury bulb. The thermometers should be inserted into a water bath to the proper immersion depth of the mercury standard and the readings of the two thermometers compared, To minimize inaccuracies caused by temperature gradients, the water should be stirred vigorously or circulated in a thermally insulated container. At least three comparisons should be done, spanning the

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temperature range for which the thermometry system is to be used.

Thermometry systems having their own calibration wells should also be checked for accuracy. A recommended procedure involves calibrating the thermometry system by use of its own well. Thereafter, the accuracy of the system should be checked with an NBS traceable standard as outlined above.

In each case, the accuracy of the thermometry system should lie within the limits specified by the manufacturer. Deviations from the specified accuracy may indicate that the equipment is unreliable and should be returned to the manufacturer for repair.

2.   Sources and Magnitude of Measurement Error

Temperature measurements in hyperthermia are especially susceptible to errors since such measurements are often taken in the presence of strong electromagnetic or ultrasound fields.[27,36] In the following, the major sources of error will be explained and methods for dealing with the ensuing problems will be suggested.

First, electromagnetic (EM) fields within the treatment room may interfere directly with the sensitive electronics of the readout unit which converts the signals from the temperature sensors to temperature readings.[7,8,10,11,25] One must keep in mind that such signals are very weak; a typical thermocouple probe generates only 40 uV/°C. Temperature probes with metallic leads as well as AC power cords can act as effective antennas for picking up FM energy and transmitting it to the readout unit. Such direct interference can be reduced substantially by proper shielding of the readout unit and by careful filtering of all incoming signal and power lines.[7,29] A good thermometer for hyperthermia should incorporate such features.

The presence of direct electromagnetic interference can be detected readily by a sudden change in the temperature reading when the hyperthermia apparatus is turned on.[8,16] When the apparatus is turned off, the reading should change in the opposite direction an equal amount.(see Figure 2a) The error due to direct electromagnetic interference can be positive or negative, i.e., the thermometer may read higher or lower
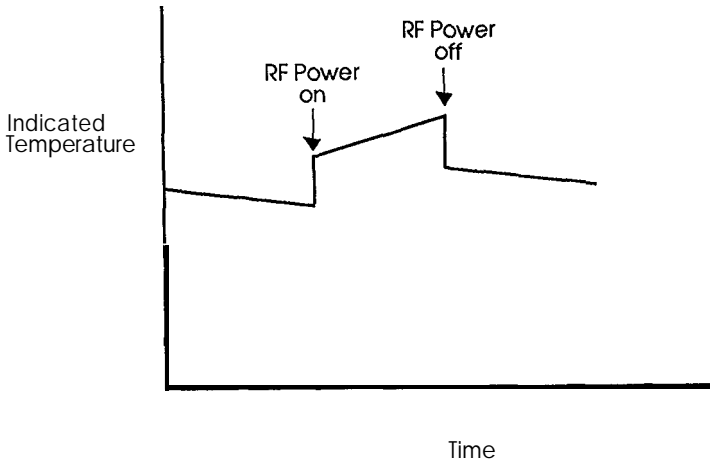
Figure 2a: An example of the effect of direct electromagnetic interference
on the indicated temperature
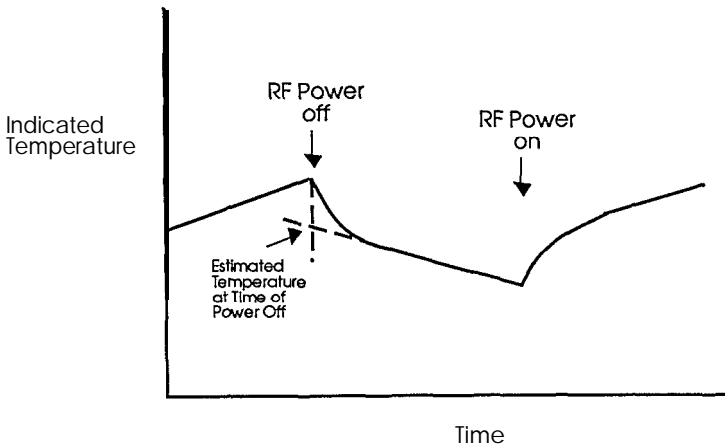
Figure 2b: Typical response of a temperature probe exhibiting
electromagnetic interference or probe heating.

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than it did before the hyperthermia apparatus was
turned on. A direct interference error can also be
identified by its strong dependence on the spatial re-
lation between the thermometer and the hyperthermia
equipment. If the electromagnetic interference is
large, especially if it drives the thermometer reading
out of range, frequent calibrations will be required
to establish that the instrument can tolerate such
strong interference without damage.

A second error can arise during hyperthermia if
the temperature probe (or the catheter) absorbs energy
more rapidly than the surrounding tissues. In this
case the sensor will become hotter than the body tis-
sues and the measurement, although showing the correct
sensor temperature, will be higher than the unper-
turbed tissue temperature. [8,16] Plastic encased temper-
ature probes, for example, are particularly suscepti-
ble to this t e of error when used in US
fields [7,20,30,33,35] Because of the high rate of US en-
ergy absorption by most plastics, the casing will
overheat and transmit the high temperature to the
sensing element.

A third type of error can arise if the tempera-
ture probe perturbs the US or electromagnetic field
and thereby alters the tissue temperature. [9,10,14] A
typical example for this problem is the tissue heating
around a thermocouple in microwave or RF hyperthermia.
At high frequencies capacitive RF currents can be in-
duced in the thermocouple wire. The ensuing concen-
tration of RF current flow in the immediate vicinity
of the thermocouple will lead to a corresponding in-
crease in tissue temperature. While the indicated
readings will represent correct tissue temperatures,
the highly localized hot spots will be poor indicators
of the prevailing temperature within the tumor.

The presence of the latter two error sources can
be detected by an initially rapid rise of the indi-
cated temperature occurring immediately after the hy-
perthermia apparatus has been turned on (Figure 2b).
After the equipment has been turned off, a similar
rapid drop in the temperature indication will occur,
often with a decay time of a few seconds. If such er-
rors are found to be present, all temperature readings
during clinical hyperthermia should be taken while the
heating power has been interrupted briefly. [20,29] How-
ever, a small error will always remain since it will

be difficult to distinguish precisely between the
"tail" of the initial rapid temperature drop and the
more gradual normal cooling of the tissues.   Extrapo-
lation to the correct tissue temperature at the time
of power off is therefore inaccurate.   If this sudden
change exceeds one or two degrees C, temperature mea-
surements will become unreliable and a better suited
thermometer should be used.

        Another source of error is introduced by the
thermal conductivity of temperature probes, especially
metallic probes.   The result is poor spatial accuracy
and is especially noticeable in regions of high ther-
mal gradient.[8],[15],[35]

        Finally, mechanical distortion of temperature
probes can affect the measurement.   Specifically,
bending some fiber-optic probes can introduce error.

        Note: Because the accuracy of temperature mea-
surements depends not only on the thermometer but also
on the hyperthermia equipment and its configuration,
the performance of a thermometry system should always
be evaluated in conjunction with the hyperthermia ap-
paratus to be used later for patient treatments. One
should carry out the evaluation under simulated clini-
cal conditions which might be expected to produce max-
imum measurement error.

C.   Generators and Power Measurement Devices

    1.   RF Generator

        The RF generator must be capable of producing
the full output power specified by the manufacturer at
all intended operating frequencies.   Output power
should be controllable from virtually zero to maximum
in a smooth or stepwise fashion.   The generator should
be connected through an appropriate power meter to a
matched load (typically 50 ohms) for all tests (see
Figure 3).   The operating frequency should be checked
with a digital frequency counter or an oscilloscope.

        For a generator to be suitable for clinical hy-
perthermia it must be capable of tolerating some
impedance mismatch.   If the manufacturer specifies the
generator to be immune to any impedance mismatch, one
should test this capability by connecting the output
to an in-line power meter.   When the output side of
the power meter is left unconnected, an infinite load

```
┌──────────────┐        ┌──────────────┐        ┌────────┐
│      RF      │ ────▶  │    Power     │ ────▶  │  50 Ω  │
│  Generator   │        │    Meter     │        │  Load  │
└──────────────┘        └──────────────┘        └────────┘
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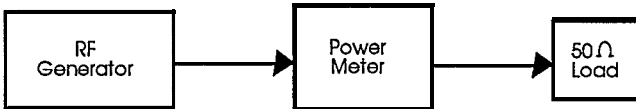
Figure 3: Block diagram of a hyperthermia generator connected through a power meter to a matched 50-ohm load.

impedance is achieved, while a short-circuited output represents a zero-impedance load. For both conditions the output power control of the generator should be gradually increased from its minimum to its maximum position and the indication of the power meter observed. The performance of the generator can be considered satisfactory if the power meter follows smoothly the position of the power control, and there is no evidence of oscillation or frequency instability.

If the generator is not fully immune to impedance mismatch, tests should be performed to verify that it complies with the manufacturer's specifications. In the absence of such specifications, open circuit and short circuit tests should be done as described before, except that the selected power level should not exceed 10% of the highest available output power. Equipment which exhibits instabilities, especially if it has the tendency to grossly exceed the output power selected by the power control or if it cannot tolerate these tests without damage, <u>should not be used</u> for hyperthermia. In a clinical setting an occasional slippage of an applicator (electrode, induction coil, etc) is virtually unavoidable. An unstable generator which responds to the ensuing change in load impedance with a sudden increase in output power is not sufficiently stable for clinical hyperthermia. However, a generator which reduces the output power in response to an impedance mismatch, or which shuts itself off completely, is acceptable.

The long-term stability of the power level should be monitored over a period comparable to a typical patient treatment (1 hour). Variations in output power should not exceed the manufacturer's specification, or 10% if not specified.

2.   RF Power Meter:

The hyperthermia apparatus should be equipped with an output power meter having an error not larger than +/-10% over the range of powers used clinically. Its accuracy should be checked against a high quality power meter connected to a suitable load resistor, or to an applicator which is coupled to a phantom. The readings of the two instruments should be compared throughout a wide range of power levels and irradiation conditions. If the power meter under test is ca-

pable of measuring forward power, reflected power, and load power, each one of these scales should be compared to the standard meter.

D.   Data Acquisition and Monitoring Systems

   1.   Evaluation Procedure

   If possible, determine the accuracy of the device to be monitored. (See previous sections) This may not be practical if the device (for example, a thermometer) is an integral part of a system which incorporates monitoring capabilities. However, individual analysis of each component of a system assures the most dependable operation. Follow the recommendations in the appropriate section of this protocol.

   Repeat several of the measurements suggested for the component to be monitored using the data acquisition system to measure and record the data. Select a range over which to test the device, which approximates clinical conditions.

   Compare the various sets of data to determine the precision of the monitoring and recording devices.

   2.   Recommended Accuracy

   Equipment used for monitoring and recording in hyperthermia systems is generally standard and conventional. The techniques used for transferring the data are likewise straightforward and uncomplicated. Consequently, no concession to accuracy need be tolerated, as might be the case for the measuring equipment itself. Monitoring and recording equipment should be accurate to within +/-1 percent of full scale for analog devices, and to within +/- one digit for digital equipment.
   The frequency of data acquisition should be determined before the instrument is placed into clinical service. Sampling rates of less than one reading (of each parameter) every 10 seconds may be inadequate for clinical use.

   The accuracy of calculation algorithms for thermal "dose"[21,49] is not easily specified. It is recommended that the user of such an algorithm compare its performance against the manufacturer's description of its operation. Discrepancies should be reported to

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the manufacturer, and use of the capability should be
suspended or moderated until the discrepancy is re-
solved. At this time, calculation procedures do not
have widespread acceptance and must be used with cau-
tion.

E. Applicators

1. External Radiative Electromagnetic Devices

a. Single Applicators

The most practical method for the evaluation of
SAR patterns of external applicators is based on the
measurement of temperature rise during a short inter-
val of time. The SAR is defined as the power absorbed
per unit mass[23], and is computed as

$$SAR = c \ \frac{dT}{dt} \qquad [W/kg],$$

where

c = specific heat of the tissue or phantom mate-
rial in J/kg°C (a typical value for muscle phantom is
3500 J/kg°C), and

dT = temperature rise (degrees C) during time
interval dt (seconds). Ideally, the temperature rise
and time interval would be true differentials. In
practice, dT/dt is approximated by $\Delta T/\Delta t$ where the
time interval is sufficiently short that conduction
effects are negligible and the temperature rise ΔT is
proportional to the time interval At.

dT can be measured either using a temperature
probe or a thermographic camera.[13](Figure 4) The
thermographic camera technique has the advantage that
the SAR pattern is obtained in a plane rather than at
a point as in a single measurement trial. This, how-
ever, is accomplished at the expense of accuracy in
the measurement of temperature rise in comparison with
the use of a temperature probe such as a thermister.[32]
Regardless of the method used, one should be aware
that SAR measurements often involve large uncertain-
ties. The measurements should be repeated several
times, and an average value determined.

Special precautions should be taken in the mea-
surement of temperature rise when temperature probes

Coaxial Cable from
EM Generator

Vertical Midplane
Separation

Applicator

Fat and Muscle
Phantom

Phantom Half
Sections

Thermographic
Camera

Midplane
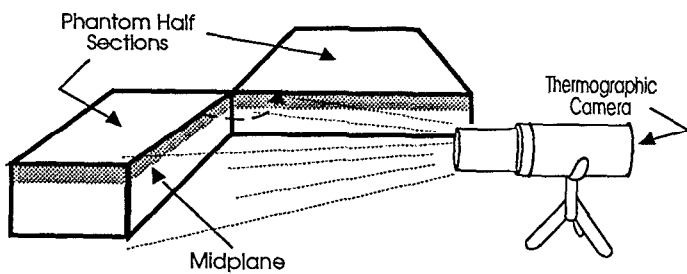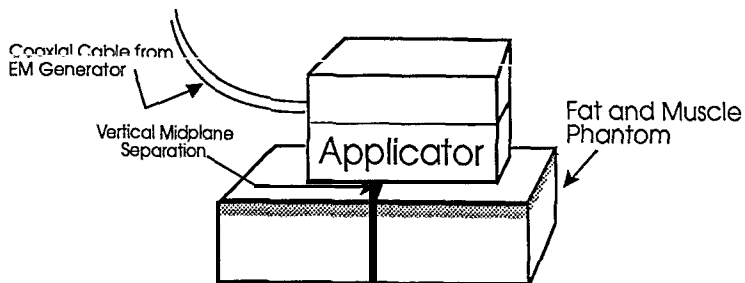
Figure 4: Measurement of the SAR pattern using a thermographic
camera and split phantom technique.

such as thermisters or thermocouples are used. Non-perturbing and interference-free probes such as high resistance thermisters or fiber-optic sensors are preferred. If ordinary thermisters or thermocouples are used the accuracy of the temperature measurement in the microwave field should be established before SAR measurements are made. (Section III.B.2.)

The temperature rise data to be used for SAR calculations should be taken from the linear portion of the temperature vs time plot (Figure 5). It is recommended that high power for short intervals (less than 30 seconds) be employed for this purpose. This is necessary to minimize effects due to thermal conduction. If the temperature at the measurement point is changing prior to power-on, one can correct for this as described by Roemer et al.[48]

i.   Phantom for SAR Measurements

For performance evaluation of most microwave external applicators, a phantom consisting of layers of fat- and muscle-equivalent material can be used. For example, a 30 cm x 30 cm x 15 cm (depth) plexiglass container filled with muscle-equivalent material, with a 1 cm thick overlying layer of fat-equivalent material is sufficient. Procedures for preparing muscle phantoms have been described by Chou[12] and Hartsgrove[26] for a wide range of microwave frequencies. The fat layer is optional and may be deleted. However, it should be understood that the fat layer may affect the coupling efficiency.

ii.   Recommended Measurements:

(1). Although a complete three-dimensional map of SAR is preferred, this may not be practical for many users. For routine measurements, at least three profiles should be obtained: The central depth profile, and two orthogonal profiles at 1 cm depth in muscle in a plane perpendicular to the depth profile. These lateral profiles should extend several cm beyond the applicator boundaries, to indicate whether hot spots exist outside the aperture.
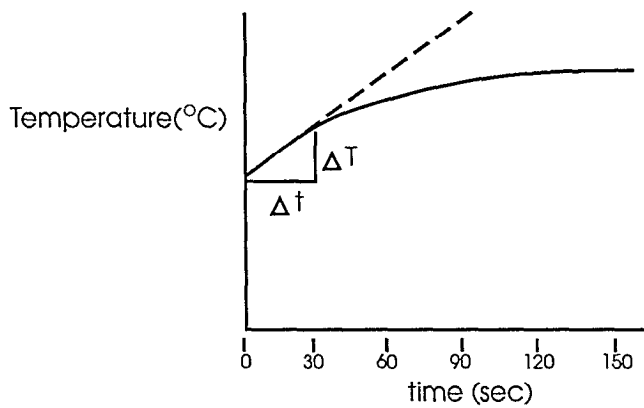
Figure 5: Determination of the temperature rise from a plot of temperature vs. time.

(2). Some applicators are designed to be oper-
ated at several different frequencies or over a
frequency range. The above measurements should
be repeated at the intended frequencies (or rep-
resentative frequencies) to cover the range of
use. This is important since the SAR pattern of
a particular applicator is likely to change with
the frequency of the applied power.

(3). The user should be aware that the attach-
ment of a coupling bolus can have a large influ-
ence on the power deposition pattern. The
procedures described here should be conducted
for arrangements which mimic the anticipated
clinical use of the equipment.

(4). The absolute value of the SAR per unit net
input power should be measured at a fixed depth
(1 cm) in muscle phantom on the central axis of
the applicator. Note that, particularly in the
case of ultrasound hyperthermia, the appropriate
reference depth may vary with the applicator and
operating conditions, and should be selected
carefully. This value should be monitored at
periodic intervals (Section IV) to assure sta-
ble, reproducible performance.

(5). Prior to using the applicator for the
first time, and whenever new treatment configu-
rations are contemplated, leakage radiation
should be measured using an isotropic probe,
calibrated near the frequency of use.[4,38] This
can be done initially with the same set-up and
power levels used for SAR measurements as de-
scribed above. Measurements of leakage radia-
tion should be made during treatments, to assure
operator and patient safety. Measurements of
power density (mW/cm^2) should be made in the
aperture plane at a lateral distance of 5 cm
from the applicator walls. Recommended limits
of leakage radiation are described in Section
G 3,38

b.   Multiple Applicator Arrays for Superficial
     Heating

Radiating-element applicators are sometimes ar-
ranged in planar arrays for superficial tissue heat-

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ing. The total SAR pattern, however, is generally not a superposition of the SAR patterns of individual elements. Instead, the array must be evaluated as an intact unit.

> i. Phantom
> The phantom to be used is again a planar model as described above (III.E.l.a.).
>
> ii. Recommended Measurements:
>
> (refer to Section III.E.l.a.)
>
> (1) For a multiple-element planar array applicator, the lateral SAR profiles should be chosen so that the space between radiating elements is covered. For example, when evaluating a rectangular arrangement of radiating elements (Figure 6a), the recommended lateral profiles are AA' BB', CC' and DD' at 1 cm depth in muscle-equivalent material.
>
> Similarly, a minimum of two depth profiles should be obtained (Figure 6b).
>
> (2) The dependence of the SAR distribution on operating frequency can be evaluated as described in section III.E.l.a. above for single applicators.
>
> (3) A measurement of the SAR per unit net input power can be made as described in section III.E.l.a. above for single applicators.
>
> (4) Measurements of leakage radiation should be made as suggested in section III.E.l.a. above.

C. Multiple Applicator Arrays for Deep Heating

The most basic array for external deep heating will likely consist of an annular ring of radiating apertures. The parameters of interest are the external electric fields within the array at the surface of the patient's body, the SAR pattern within the target volume, and the radiation leakage levels of the scattered fields around the device. A performance evaluation kit consisting of a phantom, electric field
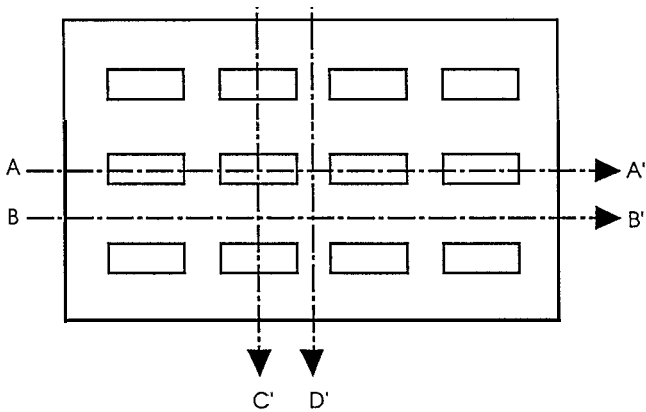
Figure 6a: The recommended location of lateral profiles for evaluating a planar array of radiating-element applicators. All profiles are at 1 cm depth in a phantom.
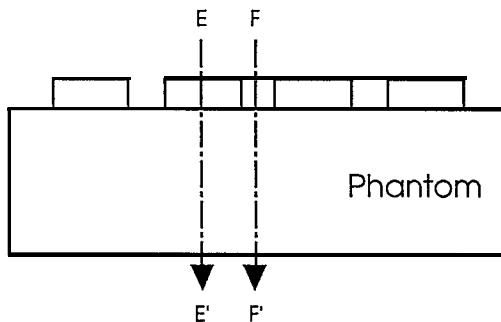
Figure 6b: The minimum recommended locations of depth profiles for evaluating a planar array of radiating-element applicators. Either profile EE' or profile FF' should pass through the center of the array.

probes and temperature probes is recommended to study these parameters.

    i.   Equipment

(1)   Phantom

    A standard torso phantom similar to the one developed by the Center for Devices and Ra diological Health (CDRH) for quality assurance of regional heating devices[5] should be used. By replacing a highly variable hyperthermic system load (the patient) with a stable load (a phantom) the relative heating capabilities can be determined under stable, repeatable conditions, with a reduced number of variables. The use of a standard phantom will also enable intercomparison of "similar" devices at different sites.

(2)   Electric field probes

    E-field probes are useful for measuring relative electric field strengths external to the patient's body and internal fields within a phantom. This is necessary to assess the symmetry of the fields. A microwave diode with its leads acting as a dipole antenna and connected to the detecting circuitry using high resistance leads can be used as an E-field probe. The probe outputs a maximum dc voltage when aligned with the electric field. The detected voltage is directly proportional to the square of the electric field strength at the measurement point. These probes are commercially available[55] and may be provided by the manufacturer of the array.

(3)   Temperature probes

    Nonperturbing temperature probes should be used for the SAR measurements. The probes should be small in diameter and long enough to permit measurements throughout the length of the phantom.

ii.   Performance Evaluation Procedures

(1)   E-field probe calibration

    The absolute magnitude of E-field probe
readings is generally less important than the
relationship between the readings of several
probes. Consequently, comparison with a stan-
dard E-field instrument is not recommended here.
Instead, the probes should be compared with each
other under reproducible conditions, keeping in
mind that the orientation of the probe to the
field may affect the reading. The phantom de-
scribed above may be used, with catheters taped
to its surface (top, bottom, and both sides) to
fix the probe position. The generator should be
adjusted to a relatively low power setting (e.g.
200 watts), and readings made at each location
with each probe. It may be useful to leave one
probe fixed while the others are moved, to moni-
tor the stability of the power level.

(2) SAR measurements

    Before attempting SAR measurements, the
output power level of the applicators should be
adjusted for symmetric (or if desired, asymmet-
ric) power deposition. The E-field probes
should be used for this adjustment. SAR mea-
surements should be made in at least three
planes; the central plane, and representative
parallel planes on either side. The SAR can be
measured by determining the rate of temperature
rise in the tissue simulating gel during a short
exposure of RF power. The temperature probes
are inserted into the catheter tracks so that
the tips lie in the plane of interest. The rel-
ative temperature rise obtained when a power of
about 600 watts is applied for about 1 minute
will give the required SAR. This procedure can
be repeated for other planes. As discussed in
section III.E.1.a., conduction effects, particu-
larly in regions of steep thermal gradient, may
be significant. If the temperature vs. time
plots indicate a non linear relationship, a
shorter time interval may be required.

(3)   Leakage measurements

        Antenna arrays for deep heating present
unusual leakage problems. Because it is more
difficult to couple the energy effectively into
the patient from multiple applicators, the rela-
tive leakage level may be higher than for a sin-
gle applicator. In addition, the overall power
applied to the array is often quite high.   These
leakage levels may cause substantial patient
heating outside the intended treatment volume,
especially in regions of small diameter such as
the head and neck and extremities.[24,55]   A survey
of the leakage radiation should consider these
locations, as well as locations likely to be oc-
cupied by the staff. Reflections from shielded
enclosures and other equipment may cause high
leakage readings at unexpected locations.

        A calibrated RF radiation hazard monitor,
suitable for the unit's operating frequency,
should be used. An isotropic probe is prefer-
able. The levels will be influenced by the type
of load in the array and the environment within
the room and these measurements can only provide
a guideline. The survey should be performed
with the phantom positioned in the array. In
addition, it will be necessary to monitor the
levels routinely during treatments.

2.   External RF Applicators

a.   Magnetic Induction Systems

        Induction hyperthermia equipment generally con-
sists of an RF power generator, an RF power meter, an
impedance matching network, one or more induction coil
applicators, a set of connecting cables, and
(sometimes) a patient support assembly. The impedance
matching network can be a separate unit, or it can be
incorporated into the applicators or the RF genera-
tors. To evaluate the performance of the equipment it
is recommended that the proper functioning of each of
the major components be evaluated separately. There-
after, the performance of the entire system should be
checked on a phantom, using a setup typical for the
intended patient treatments. If the individual com-
ponents of the apparatus are not easily accessible, a
thorough check of the entire system can be substituted

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for the performance evaluation of the individual com-
ponents. In that case, the system performance should
be tested over a broad range of anticipated treatment
situations. These tests should include operation at
all intended RF frequencies with phantoms simulating
large and small patients.

The need to evaluate the performance of the com-
plete system is due to the fact that the interaction
between the individual components (matching network,
applicators, generator) can lead to unexpected prob-
lems. For example, an RF generator may work perfectly
when its output is connected to a shielded load. In
an actual hyperthermia treatment, however, the large
RF applicators together with the patient act as power-
ful transmitting antennas. Unless the oscillator and
other low power components within the RF generator are
properly shielded, a positive feedback loop can de-
velop, causing the system to go into uncontrolled
self-oscillations. This can cause the RF generator to
behave erratically, possibly producing its full output
power, regardless of the setting of the output power
control. The frequency of such self-oscillation may
be different from the normal operating frequency of
the hyperthermia system.

i.   RF Generator and RF Power Meter

The performance of these units should be
evaluated as described in section III.C.

ii.   Inductive Applicators

Induction coils should be inspected visu-
ally to assure that their construction complies
with the manufacturer's specifications. Consid-
ering the high voltage and power levels present
in many induction coils, particular attention
should be paid to the adequacy of the insula-
tion. Although high frequency currents at the
power levels used in hyperthermia are generally
not life-threatening, they can cause painful
burns to the patient or the operator. Because
of the strong interaction between the various
components and the patients, applicators should
be tested as part of the system evaluation.

iii.   System Performance Evaluation

After the hyperthermia system has been
fully assembled it should be tested on a suit-
able phantom. Because inductive hyperthermia
systems generally operate in the frequency range
of 1 MHz to 27.12 MHz, a phantom can be made
easily from tap water by dissolving in it 4.4 g
table salt per liter. The so-formed saline so-
lution can be contained in any electrically non-
conducting container having suitable dimensions.
The geometrical shape of the phantom should re-
semble the shape of the patient region to be
treated, but does not need to include areas
where the magnetic field strength is less than
10% of its maximum within the patient. For ex-
ample, a 10 cm diameter surface applicator to be
used for treatments at 3 cm depth or less, can
be checked by placing it against the surface of
a 15 cm cubic container of saline solution. The
magnetic field-intensity beyond the container
will be negligible, and one can therefore expect
very little variation in the outcome of the test
if the dimensions of the container are in-
creased.

b.   Capacitive Heating Systems

Capacitive hyperthermia equipment generally con-
sists of an RF power generator, an RF power meter, an
impedance matching network, a set of electrode appli-
cators, a temperature control system for the applica-
tors, a set of connecting cables and water cooling
hoses, and a patient support assembly. To evaluate
the performance of the equipment, it is recommended
that the proper function of each of the major compo-
nents be evaluated as a system, for reasons discussed
earlier. (Section III.E.2.a.).

C.   Temperature Control System (TCS):

Most capacitive hyperthermia systems will be
equipped with provisions for controlling the tempera-
ture of the electrode applicators via circulating wa-
ter. The performance of the TCS should be evaluated
with the hyperthermia system fully assembled and the
RF power adjusted to levels ranging from zero to typi-
cal clinical values. It should be verified that the
TCS is capable of controlling the electrode tempera-

ture within the full range specified by the manufacturer. The time required to respond to changes in the selected electrode temperature should also be recorded and compared to the specifications (if available). A surface temperature probe of reasonably high quality can be used to measure electrode temperatures. Good contact between the probe and the electrode is required.

3. Interstitial and Intercavitary Electromagnetic Applicators

a. Interstitial Microwave Antennas

1. System Considerations

Optimum tissue heating is dependent upon the division of RF power among the antennas. The operation of the power distribution system should be evaluated with all outputs terminated with either a dummy load or an applicator and a phantom, and with the power distributed equally among the channels. (Refer to Section III.C for recommended power measurement procedures.) A through-line power meter can be inserted between the generator and antenna of the channel to be tested. The measurements should be made with the generator adjusted to 25, 50, and 100% of its maximum power, to demonstrate linearity of power distribution. All outputs should be tested in this way, and each should fall within 10% of the mean value. Systems which exceed this tolerance should be serviced or replaced.

All coaxial cables should be inspected regularly for power loss, cable or connector heating, or loose connectors. Visual inspections play a major role, but measurements should also be made of reflected power when the cables are terminated with a 50 ohm load. Under these conditions, reflected power levels exceeding 10 or 20% are indicative of physical damage to the cables or connectors.

The temperature monitoring and control systems should be tested according to section III.D.

ii.   Antenna Considerations

       As with external applicators, interstitial
antennas should be matched properly to the tis-
sue or phantom and the generator. Reflected
power less than 10% of the forward power indi-
cates acceptable matching.

       Antennas should show comparable and con-
sistent heating in a tissue-equivalent phantom.
A measurement of SAR should be made at a point 5
mm from the antenna axis, at the point of maxi-
mum SAR. The value determined should be com-
pared with the measurement made when the probe
was new. A value of approximately 30 W/kg per
watt of applied power is typical of some de-
signs.

       The relative SAR pattern also should be
measured, for comparison with data provided by
the manufacturer. Heating times should be kept
as short as possible (30 seconds is reasonable).
At a minimum, the SAR should be measured along a
line parallel to the antenna, at a distance of 5
mm away from the axis. The antenna should be
inserted into the phantom to a depth comparable
to that used for clinical treatments. The sen-
sitivity of the heating pattern to the depth of
the antenna should be investigated, as extreme
surface heating may occur with incorrect depths.

b.   Interstitial RF (Localized Current Field)

    i.   System Considerations

       Begin by ensuring that the RF power is di-
vided properly among all channels activated, and
that the reflected power is reasonable. A power
meter and a 50 ohm load should be used as de-
scribed in part III.E.3.a.i (above). Next, in-
vestigate the time sequencing or duty cycle con-
trol of the channels. A visual inspection of
all indicators and switches should be performed.
The accuracy and linearity of the cycle timing
can be determined by displaying the output wave-
form with an oscilloscope. (A bandwidth of at
least 10 MHz is recommended.) Ensure that there
are no switching transients or current over-
shoots which exceed 10% of the output amplitude.

The output should also be measured with both
open and short circuit conditions. The design
of the equipment should minimize the risk of de-
velopment of electric current paths not intended
for treatment. Likewise, the user should be
aware of the possible electrical hazard to the
patient in the event that an electrode should
become disconnected.'

Refer to Section III.G for electrical
safety measurements, and to Section III.D for
temperature monitoring and control functions.

ii.   Hardware Considerations

Several visual inspection procedures can
help assure proper operation of the hardware.
All cables should be checked for physical dam-
age, and connectors should be clean and tight.
Reusable electrodes must be straight and sharp,
and without damage to the insulation. In most
situations, electrodes must be parallel for op-
timum heating, so bent or kinked electrodes
should be discarded.

c.   Interstitial Ferromagnetic Seeds

Proper heating of interstitial seeds depends
upon correct operation of the inductive heating appa-
ratus. Refer to section III.E.2.a. for procedures for
evaluating the heating equipment. Refer also to Sec-
tion III.B for procedures for evaluating the ther-
mometry system.

The thermoregulating temperature of curie-point
ferromagnetic seeds may be investigated in a phantom.
A suitable thermometer probe may be positioned at 5 mm
radius from the midpoint of the seed. Sufficient RF
power should be applied to reach the thermoregulation
mode, and maintained for a predetermined interval (at
least 10 min). The temperature reached should be con-
stant to within 2%. Compare the temperature at the
reference point to the original seed performance; ad-
just the thermal dosimetry (ferro-seed spacing) ac-
cordingly, or discard the seed. Bent seeds should be
discarded, as they may not heat properly.

4.   External Ultrasound Heating Systems

a.   Generator

RF generators for ultrasound (US) hyperthermia operate in the frequency range from 300 kHz to 5 MHz. Because transducer operating characteristics usually are extremely sensitive to generator frequency, the performance requirements are stringent.

i.   Frequency

As the character of the near field is very sensitive to frequency, the frequency of the generator should be known to within 1.0 kHz, and should be stable for no less than the duration of a typical heating session (a minimum of two hours is recommended). A calibrated frequency meter should be used. The generator frequency should be adjustable throughout a range which includes the nominal resonance frequency +/-10% for each transducer associated with the system. The range will accommodate variations in operating parameters sometimes required to reduce near-field effects.

ii.   Electrical Power

Requirements for and evaluation of US generators are similar to those for generators for RF heating systems, and include investigation of electromagnetic interference (EMI). Refer to Section III.C for recommended specifications and measurement procedures.

b.   Single-Transducer Systems

i.   Acoustical Power

The relationship between electrical power and acoustical output for a given transducer is sometimes non-linear at high power levels. Consequently, it is necessary to characterize each transducer over a range of representative power levels, for each nominal operating frequency.[31] An US wattmeter or radiation force balance should be used. Next, the dependence of acous-

tical power on frequency should be determined.
The peak acoustical power should occur at a fre-
quency falling within 10% of the nominal operat-
ing frequency (selected to suppress near-field
effects, while at the same time having ac-
ceptable output power and efficiency). During
this test, it is advisable to operate the gener-
ator at a level corresponding to an acoustical
power output of approximately 50% of the maximum
achievable. Heating of the transducer element
itself is normal, and may affect the relation-
ship between acoustical output and electrical
input power. This relationship should be mea-
sured as a function of time of operation at high
power. If transducer heating causes a change in
the relationship of more than 5%, adjustments to
the transducer cooling system should be made.

ii.   SAR Measurements

As with RF applicators, a full three-di-
mensional map of the power deposition pattern is
desirable, but impractical. In practice, a mea-
surement of peak SAR at a reference location is
combined with longitudinal and transverse pro-
files of relative power deposition.

The SAR should be measured in a tissue-
equivalent phantom[17] using bare thermocouples
fixed at a multiplicity of spatial points. Al-
ternatively, this may be done by mapping tight-,
fitting probes in good thermal contact with very
thin-walled stainless steel needles embedded in
the phantom. This latter technique will lead to
some thermal smearing which must be assessed
(section III.B.2.) If a tissue-equivalent liq-
uid[18,44] (or water) phantom is used, the relative
power deposition profile can be made rapidly us-
ing an RTV-encapsulated thermocouple[19] or a
miniature hydrophone. Refer to Section III.E
for the procedure for computing SAR, and Section
III.B.2. for cautions concerning temperature
measurement errors in US fields.

The transducer should be indexed to assure
reproducible positioning, and lateral beam pro-
files should be measured at 2 cm intervals
throughout the heated volume. Scans should be
made with the transducer rotated to different

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angles, to demonstrate circular symmetry of the heating pattern. The power deposition pattern of focussed transducers should be mapped at high spatial resolution, ideally 2 mm in all directions in the vicinity of the nominal focus.

The measurements should be repeated at all frequencies intended for clinical operation, and at representative power levels for each transducer.

iii. Water Coupling System

A water system is required for good acoustical coupling, and circulation is necessary to cool both the transducer and the patient surface. The volume of water circulated must be adequate to carry out both tasks. To provide adequate control over patient surface temperature, the water temperature should be regulated to within 0.5%. The cooling water must be degassed well, particularly for operation at high power. Recommended procedures for degassing are:
- boiling for 15 minutes, or
- maintaining at a pressure of less than 30 mm of mercury for 3 hours,

less than 12 hours before use.[19,31] Inadequate degassing may result in cavitation and greatly reduced heating efficiency. Evidence of cavitation may be observed by shining a bright flashlight through the coupling water adjacent to the transducer, when operating the system in a darkened room. The user will observe the presence of minute bubbles and enhanced scattering of light.

iv. Reproducibility

Repositioning of the applicator and reproducible coupling to the phantom should be assured by repeating a phantom set-up at least five times. A measurement of SAR should be made at a reference point at both low and high power, each time the setup is repeated. The standard deviation of the measurements should not exceed 5%.

C.   Multiple Transducer Systems, and Scanning
      Systems

     Each transducer of a multiple transducer system
should be characterized as described above. Because
arrays and scanning systems can vary widely, it will
be necessary to devise tests which evaluate the repro-
ducibility and safety of representative clinical con-
figurations.

F.   Control Systems

     Improper operation of the control devices installed in
a hyperthermia system can lead to extremely dangerous situa-
tions. It is of paramount importance that the device (or
software) which controls the heat-delivering equipment re-
spond properly to the temperature or other parameter being
measured. It is difficult to analyze such a control system
in a manner which is representative of the clinical use of
the equipment without employing an animal patient or a dy-
namic phantom model.

     However, it is possible to perform the simpler analy-
sis recommended here. The procedures described below should
be conducted prior to clinical use, and at any time that the
operation of the unit is questioned. Otherwise, routine
clinical operation will demonstrate that the system is func-
tioning properly.

     All other recommended quality-assurance procedures
should be performed to ensure the proper operation of each
component. Two water baths (or similar environments with
controllable temperature) are required. The power-delivery
equipment (antennas, transducers, etc) should be arranged to
heat a phantom unrelated to the water baths. The tempera-
ture and power absorbing qualities of the phantom are not
important for this control system verification (Figure 7).

     If the control system permits regulation of the heat-
delivery equipment based on the temperature of one or more
thermometers, these thermometers and the target temperature
(say, 43%) should be designated. Similarly, if the control
system terminates heating whenever a predetermined tempera-
ture is exceeded, the maximum allowable temperature (say,
47ºC) should be designated. All thermometer probes should
be placed in one of the water baths adjusted to a tempera-
ture several degrees below the target temperature (say,
41%). The heat-delivery system should then be energized.
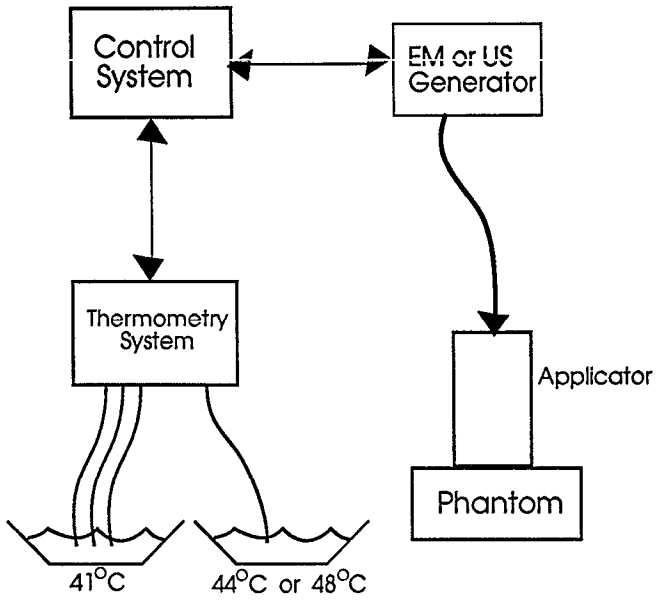
Figure 7: Arrangement for evaluating the operation of control systems.

The following test of the control system should be conducted:

      1.   Move one of the control thermometers from the 41°C water bath to a 44°C environment. Verify that the power to the heat-delivery system (or portion controlled by the thermometer which was moved) is reduced.

      2.   Replace the thermometer into the 41°C environment and verify that the power to the heat-delivery system is adjusted toward its original level.

Repeat these steps for each of the control thermometers.

The limiting capability should be tested as follows:

      1.   Place a thermometer into a 48°C environment and verify that the power to the heat-delivery system is interrupted.

      2.   Return the thermometer to the 41°C environment, and verify that the heat-delivery system can be energized readily.

Repeat these steps for each thermometer. Note that a more demanding test may be conducted by chosing water-bath temperatures which are closer to the target and limiting temperatures.

G.   Electrical and Radiation Safety

  1.   Electrical Leakage Currents

As with any electrical equipment to be used in a patient environment, hyperthermia equipment must be checked routinely for electrical safety. Test procedures for 60 Hz electrical leakage current have been described by the American National Standards Institute.[1] This standard recommends semi-annual inspection of output isolation from ground at 60 Hz and at the RF source frequency. Limits are 10 uA RMS electrode-to-ground and 100 uA RMS chassis-to-ground worst case leakage current at 60 Hz with the equipment ground Intact and Disconnected, polarity Normal or Reversed, and the unit Off or in Standby-On mode. No published standards could be found which address electrical leakage at frequencies above 1 MHz, although ANSI[1] suggests that the limits recommended at 100 kHz be applied to higher frequencies. However, the Na-

tional Fire Protection Association recognizes the need
for further study.[40] The American National Standards
Institute limits the high frequency leakage power from
electrosurgical devices to 4.5 watts.[2] This standard
may be a suitable guideline for components of a hyper-
thermia system other than the applicator.

These tests should normally be performed by the
Clinical or Biomedical Engineering house staff at each
facility who are qualified to interpret the detailed
listing of test procedures, current limits, and test
conditions recommended in the guidelines. Compliance
with these standards is especially important for hy-
perthermia equipment with direct electrical connec-
tions to the patient, such as interstitial RF elec-
trodes and implanted temperature sensing devices,
where the electrical safety hazard is greatest.

2.   Electromagnetic Radiation

Hyperthermia treatments involving the use of
high-power high-frequency generators are potentially
hazardous to both the patient and equipment operators
due to leakage of electromagnetic energy from the gen-
erators treatment applicators and interconnecting ca-
bles.[34,47] This undesired "leakage radiation" can pro-
duce significant interference with nearby sensitive
equipment such as thermometry systems and physiologi-
cal monitors. In addition to the electrical interfer-
ence problem there are potential biological hazards of
non-ionizing electromagnetic radiation, even at low
power levels.[6,28,37,38,38,39,51] Stray radiation may produce
excessive heating at sites remote from the intended
treatment site, however. Thus, the FDA's Center for
Devices and Radiological Health (CDRH) has produced
the ANSI Radiofrequency Protection Guide to establish
limits on the allowable leakage radiation around high-
frequency equipment.[3,38] While the limits are fre-
quency dependent, the standard recommends a maximum
six-minute averaged leakage power density of 5 mW/cm^2
(measured ≤ 5 cm from any chassis or applicator sur-
face) for microwave frequencies above 1.5 GHz. Even
more stringent requirements are specified for lower
frequencies and for longer exposure times. Thus,
leakage radiation should be monitored with a cali-
brated isotropic radiation survey meter during each
new procedure to comply with the regulations and to
ensure safe operating conditions.[4] Special attention
should be given to monitoring sensitive regions such
as the eyes, face or groin area. Treatment conditions

which produce leakage in excess of the limits should
be reconfigured.

IV. FREQUENCY OF EQUIPMENT EVALUATION

The following table is intended as a guide to the fre-
quency at which performance evaluation procedures should be
repeated. Similar guidelines have been published else-
where.[52,53]

Evaluation frequencies are specified for two condi-
tions: For equipment that is operating normally and has
demonstrated its reliability, a "normal minimum" frequency
of evaluation is suggested. Equipment which has not yet
demonstrated such reliability or which exhibits unstable or
erratic behavior should be evaluated more often, at no less
than the "initial recommended" frequency. In addition, the
evaluation procedures should be conducted whenever damage to
the equipment is suspected, and also when a piece of equip-
ment is returned to service after a hiatus exceeding the
"initial recommended" frequency, or following repair or mod-
ification.

PERFORMANCE EVALUATION FREQUENCY

SECTION	ITEM	INITIAL RECOMMENDED FREQUENCY	NORMAL MINIMUM FREQUENCY
III-A	Visual Inspection	Prior to each treatment	Beginning of each treatment day
III-B	Thermometry Equipment	Prior to each treatment	Weekly, or follow manufacturer's recommendations
III-C-1	RF Generator	Monthly	Annually
III-C-2	RF Power Meter	Weekly	Annually
III-D	Monitoring and Recording System	Prior to each treatment	Weekly
III-E	Applicators		
	SAR at reference point	Weekly	Semiannually
	Power deposition distribution	Monthly	Annually
III-F	Control Systems	Daily	Monthly
III-G	Electrical Safety	Prior to use	Following Service or Semi-Annually
	EM Radiation Safety	During each treatment	With each new setup

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