Ionization Chamber Instrumentation

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Ionization chambers

- These instruments are the basic instrumentation for Therapy Medical Physicists. (e.g. TG 51 - discussed next)
- First ion chamber was an electroscope
  - Gold leaves suspended in air.
  - Amount of separation of leaves decreases as ionization occurs in air.
Electroscope
Example with leaves collapsed
Steps in Ionization Chambers

- Next step for ionization chambers was to put the electroscope in a container with a “thimble capacitor” with readout.
- This was a condensor meter or the old Victoreen R meter.
Ionization Dosimeters

- Next step was a permanently connected chamber - cable connecting chamber and readout - the Radacon
Now chamber and electrometers are separate
High precision Ionization chambers
Require calibration
Primary standards will be discussed later on Wednesday.
Uncertainties remain small
Therapy Chambers

- Generally 0.6 cc for photon beams. Calibrated for air kerma or absorbed dose to water at cobalt.
- For electrons parallel plate chambers are used, calibrated for air kerma or absorbed dose to water at cobalt.
- Chambers in use need corrections applied as in Protocols (TG51, TG 61)
Calibration

- Calibration of chambers should be done across the energy range of use. For therapy this calibration is at cobalt 60.
- Generally there is a reference energy in use.
Calibration

- Air kerma calibration usually designated $N_K$ and absorbed dose to water is designated $N_{60Co}^{60Co}$.
- Calibration factor (coefficient). A coefficient has units - a factor is dimensionless.
- For both of the above it is a Calibration coefficient.
Purpose of the Electrometer

- Applies voltage to create an electric field in the ionization chamber
- Measures the charge (or current) produced resulting from the ionization of the mass of material in the cavity
- Electrometer needs calibration also.
Calibration for Electrometers

- If readout is in terms of Coulomb or Amp, it would be C/”C” or a calibration factor.
- However, “C” is not “true” coulombs and thus, the calibration is given as C/Rdg to avoid confusion.
- In this case it also would be a calibration coefficient.
Schematic of thimble ionization chamber connected to electrometer.
Operation of chamber

- Volume of chamber determines the size of the signal.
- Volume determined by guard
- Fully guarded - guard extends into air volume of chamber
- Partially or minimal guard - how much does guard extend into air volume.
A Farmer chamber

- thimble
- electric field
- HV Insulator
- collector
- guard
Field lines for a parallel plate chamber
Parallel Plate schematic

- Electric field
- Window
- Collector
- Guard
- HV insulator
- \( r_g \)
- \( r_c \)
- \( d_{\text{gap}} \)
- \( g \)
Guard and volume

- Field lines pinch - the larger the guard and smaller the gap the better the pinch
- Rule of thumb: guard should be $\geq 3$ times the gap
- Volume defined by half the gap, so for parallel plate chambers
- $\text{volume} = \pi g \left[ 0.5(r_g + r_c) \right]^2$
Schematic for spherical Chamber

- Shell
- Collector
- Guard
- HV Insulator
- Electric Field
The effect of guarding: Limitation to a known volume
Guard

- Desire is to collect charge from a known and well maintained volume. Not random amounts of ionization outside the chamber.
- Added advantage is reduction of leakage and other effects
Stem Effect of Chambers

- Response from stem not thimble
- Depends on guarding: in particular the length of the unguarded stem
- This is a function of the energy (and of course, the size of the beam).
- Sometimes it really is a cable effect and not caused by the chamber
### Some typical Chamber stem effects

<table>
<thead>
<tr>
<th>Type of chamber</th>
<th>Length of unguarded stem (cm)</th>
<th>Stem Effect in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unguarded</td>
<td>7.0 to 8.5</td>
<td>0.3 to 0.6%</td>
</tr>
<tr>
<td>Guarded</td>
<td>1.0 to 1.5</td>
<td>0.1 to 0.3%</td>
</tr>
<tr>
<td>Well Guarded</td>
<td>&lt; 1.0</td>
<td>&lt; 0.1%</td>
</tr>
</tbody>
</table>
Desired Cable Characteristics

- Fast equilibration time with change in High Voltage
- Low radiation induced signal
- Low microphonic noise
- Low leakage (<10^{-14}A - today even 10^{-15}A)
- Pliable
- Easy and sturdy connector installation
- Low capacitance per meter
Leakage

- Measure leakage on system, before charge collected and with charge or reading. Generally most of the leakage is caused by the cable.
- Measure leakage on electrometer, before charge and with charge on it. Generally most good electrometers have < 1fA leakage.
Chamber leakage

- The major challenge is where is the leakage coming from
  - Chamber
  - Electrometer
  - Cable
- Leakage in the chamber is generally 1 to 10 fA for a good chamber.
The chamber wall

- $K_{\text{wall}}$ is a factor to correct for attenuation and scatter in the wall before the air cavity.
- It accounts for both the wall of the chamber and the buildup cap.
Characteristics of Chambers

- Ion collection efficiency: The charge collected versus the charge produced.
- There is a difference because of recombination of positive and negative ions in the gas before being collected.
- The desired result is to have saturation and it depends on the bias voltage.
Chambers and increasing Voltage

- The operation of the chamber changes as the voltage increases.
- At very low voltage, less than 50 volts: (this depends on the chamber of course) this is the area of recombination.
Ion chamber response with V
Chambers with voltage

- At low potentials, - up to 500 to 800 V, the system will operate as an ionization chamber and an ionization registers the total charge carried by the ionization
- This has a plateau (the saturation region)
- As the potential is increased, the electrons gain sufficient energy to initiate ionization in the filling gas. This results in stages of electron multiplication
Chambers with voltage

- This electron multiplication results in a gain of several orders of magnitude.
- This is the proportional counting region.
- There is no interaction between the "avalanches" along the length of the collector and the signal is proportional to the number of electrons released.
Continual increase in voltage

- The region of limited proportionality is entered where the avalanche becomes more “spread out” and the proportionality begins to break down.
- As voltage increases, another “plateau” is reached where an avalanche initiates another avalanche and one event fills the gas with ionization products.
The pulses are of uniform size no matter what radiation is being detected. The amount of radiation only depends on how many pulses within a time period.

If the rate is too high, the GM counter will have a dead time that extends beyond the deposition of radiation.
Voltage Curve for Typical Ion Chamber

The graph shows the relationship between the applied potential and the relative pulse height. It highlights different regions such as the ion chamber region, proportional counting region, limited proportional region, and Geiger-Müller region. The curve illustrates the threshold for multiplication and the transition to continuous discharge.
Ion chambers

- Generally they operate in the near saturation or saturation region.
- When the chamber is below saturation, some of the charges in the chamber are lost by recombination.
Recombination

- There are 3 mechanisms
  - General recombination: opposite charges from different tracks collide and recombine
  - Initial recombination: opposite charges from the same tracks collide and recombine
  - Ionic diffusion loss: charges diffuse against the electric field.
The correction factor $k_{\text{sat}} (A_{\text{ion}} \text{ or } P_{\text{ion}})$ differs when it is continuous radiation (cobalt), a pulsed beam (many linacs) and scanned pulsed beams (linacs that produce their beams by scanning the electrons across the target.)

See Podgorsak pp314-318 for equations.
An approximation is to measure charge $Q_1$ at full voltage (300V) and charge $Q_2$ at half voltage (150V).

A quantity termed $A_{ion}$ which is the inverse of the ion collection efficiency is then determined from:

$$A_{ion} = \frac{4}{3} - \left(\frac{Q_1}{3Q_2}\right)$$
Most chambers do not exhibit polarity differences

- Polarity is collecting negative charge with +300 V and then collecting positive charge with -300 V
- If there is a significant difference the chamber may have a problem
Polarity in electron beams

- Protocols ask that an electron beam be measured with positive and negative polarity.
- This is then averaged for the reading.
- This is to account for differences caused by the electron negative charge contributing to the signal.
Energy Response

- It is desired to have a uniform energy response for all energies.
- The window or wall is very important for the energy response.
- Generally a chamber is designed for a region to be within a given percentage.
Energy Response Farmer type
Major corrections for Ion chambers

- Ion chambers need some corrections but the major correction is for air density
- Air density. $T = \text{temperature}$, $T_0 = \text{standard temperature}$, $P = \text{pressure}$, $P_0 = \text{standard pressure}$
Other Ionization Chambers

- Chambers discussed up to now are air communicating (generally not sealed on purpose)
- Some chambers use flow of specific gases to detect particulate radiation (Protons)
Brachytherapy Ionization chambers

- Brachytherapy measurements done with specialized well chambers
- Repeating measurements of same source give reproducibility of <1%
Schematic of typical well chamber
Typically calibration of well chambers involve using a single seed at the axial maximum (sweet spot).

The insert is a very important part of the calibration.

A calibration factor is necessary for each source type calibrated.
Characteristics of Well Chambers

- Well chambers have an axial maximum (sweet spot)
- The size of the sweet spot should be known.
- It is not a problem if the source length is small enough.
Response with Length for a Well Chamber
Extended Length Sources

- Problem with extended length sources is the “fall off” of the sweet spot due to axial geometry limitations
- Modifications have been made to chambers to obtain an extended “sweet length”
Typical Sweet Lengths

![Graph showing signal relative to maximum vs. distance from center in mm]

- The graph illustrates the variation of signal relative to maximum with distance from the center.
- The curve peaks at the center and decreases symmetrically on either side.
Items to Maintain Well Chambers

- Set up a QA check, using another known source: Cs needle, cobalt unit, accelerator
- Account for any leakage if it is significant. Keep in mind that there may be other sources contributing to background that could look like leakage.
Vented chambers

- Gas Density corrections need to be made
- Overcorrection occurs at lower pressures for low energy photons
- Simply caused by measuring all ionization - Aluminum wall creates ionization such that all is absorbed in first chamber of well
The standard $C_{TP}$ correction is sufficient to normalize chamber response to standard atmospheric pressure.
Photons in Pressurized Chambers

- When used with photon sources the pressurized chamber needs no $C_{TP}$ correction and exhibits the same response regardless of the ambient pressure.
Beta Radiation in Pressurized Chambers

- The response of pressurized chambers is not constant.
- May be due to decreased attenuation of the betas by the low-pressure air.

![Graph showing the response of pressurized chambers with different isotopes of Sr and P.](image)

**Graph Details:**
- The x-axis represents pressure (Torr) ranging from 500 to 850.
- The y-axis represents the response normalized to 760 Torr, ranging from 0.97 to 1.03.
- Two lines are plotted:
  - Chamber with $^{90}\text{Sr}$.
  - Chamber with $^{32}\text{P}$.

The graph visually demonstrates the variation in response with pressure for the two different types of chambers.
Beta Radiation in Air-Communicating Chambers

**Fig. 5:** The average response of the HDR1000 Plus and the IVB1000 to two beta emitting sources is plotted as a function of pressure. The response has been $P_{\text{ref}}$ corrected and is normalized to the value at 760 torr.
Low-Energy Photons in Air-Communicating Chambers

- Applying only $C_{TP}$ over-corrects the response
- The over-correction increases in magnitude as the photon energy decreases
## Magnitude of Over-Response

<table>
<thead>
<tr>
<th>City</th>
<th>Elevation</th>
<th>TheraSeed Over Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mexico City, Mexico</td>
<td>7350 ft</td>
<td>16%</td>
</tr>
<tr>
<td>Denver, Colorado</td>
<td>5300 ft</td>
<td>11%</td>
</tr>
<tr>
<td>Salt Lake City, Utah</td>
<td>4390 ft</td>
<td>9.2%</td>
</tr>
<tr>
<td>Kathmandu, Nepal</td>
<td>4260 ft</td>
<td>8.9%</td>
</tr>
<tr>
<td>Billings, Montana</td>
<td>3140 ft</td>
<td>6.5%</td>
</tr>
</tbody>
</table>

**Table I:** As altitude increases and therefore ambient pressure increases, the over-response becomes an increasingly large percent of the total reading for the HDR1000 Plus and the IVB1000.
Pressure Correction, $C_A$

- The altitude correction is: 
  \[ C_A = k_1[P]^{k_2} \]
  where the proposed coefficients for two chambers are:

<table>
<thead>
<tr>
<th>Seed</th>
<th>HDR and IVB</th>
<th>WC-2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$k_1$</td>
<td>$k_2$</td>
</tr>
<tr>
<td>TheraSeed 200</td>
<td>0.0241</td>
<td>0.562</td>
</tr>
<tr>
<td>Amersham 6711</td>
<td>0.0490</td>
<td>0.455</td>
</tr>
<tr>
<td>SourceTech STM 125I</td>
<td>0.0573</td>
<td>0.431</td>
</tr>
</tbody>
</table>

- Making the total correction for temperature and pressure involves multiplying this value times T-P correction.
The correction factor for ambient pressure, $C_A$, is necessary for air-communicating ionization chambers with aluminum components.

Plastic chambers such as the RPC chamber do not appear to require correction beyond $C_{TP}$.

Air-communicating chambers do not require correction for high-energy photons or beta radiation. A small correction for beta is necessary for pressurized chambers.
Other chambers

- Med Phys 34: 4690 (2007) shows that this pressure effect is also valid for thimble type ion chambers used for kilovoltage x-rays.
- This effect also is present depending on the materials used for the chamber walls and collector
## Regular Ion chambers and materials

<table>
<thead>
<tr>
<th>Chamber</th>
<th>Wall Material</th>
<th>Thickness (mm)</th>
<th>Electrode Material</th>
<th>Nominal collecting volume (cm³)</th>
<th>$L=4V/S$ (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NE 2571</td>
<td>Graphite</td>
<td>0.36</td>
<td>Aluminum</td>
<td>0.6</td>
<td>0.48</td>
</tr>
<tr>
<td>NE 2505/3</td>
<td>Graphite</td>
<td>0.36</td>
<td>Aluminum</td>
<td>0.6</td>
<td>0.48</td>
</tr>
<tr>
<td>(modified)</td>
<td>Dural</td>
<td>0.09</td>
<td>Aluminum</td>
<td>0.7</td>
<td>0.52</td>
</tr>
<tr>
<td>Exradin A19</td>
<td>C-552</td>
<td>0.5</td>
<td>C-552</td>
<td>0.6</td>
<td>0.46</td>
</tr>
<tr>
<td>Exradin A12</td>
<td>C-552</td>
<td>0.5</td>
<td>C-552</td>
<td>0.6</td>
<td>0.54</td>
</tr>
<tr>
<td>Exradin A2</td>
<td>C-552</td>
<td>1.0</td>
<td>C-552</td>
<td>0.7</td>
<td>1.24</td>
</tr>
<tr>
<td>(modified)</td>
<td>C-552</td>
<td>1.0</td>
<td>Aluminum</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aluminum</td>
<td>1.0</td>
<td>C-552</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aluminum</td>
<td>1.0</td>
<td>Aluminum</td>
<td>0.7</td>
<td></td>
</tr>
</tbody>
</table>
Various chambers: note materials
Note effect of materials

![Graph showing the effect of materials on particle density ratio](image)

- **Al wall**
- **Al wall & electrode**
- **Al electrode**
- **C-552**

Exradin A2
60 kV

\[ \frac{[M(\rho) \times P_{T_{pl}}]}{M(\rho_0)} \]

\[ \frac{\rho}{\rho_0} \]
Effect of Pressure

- Note the dependence of the wall material and electrode.
- Air equivalent material has no real effect.
- Corrections (if significant) should be made.
Important Points for the Physicist

- A knowledge of the equipment dealt with, and of its calibration parameters.
- Care in how the equipment is used and the variability of parameters.
- Attention should be paid to quality assurance procedures so traceability at the lowest uncertainty is maintained.