TG-191
The clinical use of luminescent dosimeters

THE UNIVERSITY OF TEXAS
MD Anderson Cancer Center
Making Cancer History®

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Scope of Report

This report aims to address the following charges as they pertain to luminescence dosimetry:

- **Review the variety of TLD/OSLD materials available, including features and limitations of each**
- **Outline optimal steps to achieve accurate and precise dosimeters and assess the associated uncertainty**
- **Develop consensus guidelines for the optimal use of luminescent dosimeters for clinical practice**
- **Develop guidelines for special medically relevant uses of TLD/OSLD.**

Status of Report

- Reviewed by WGRD
- Reviewed by SC
- Still needs final review by TPC

- Published 2017

Goals of this session

- Convey TG summary:
  - Listen to this talk now so you don't have to read the TG report later!

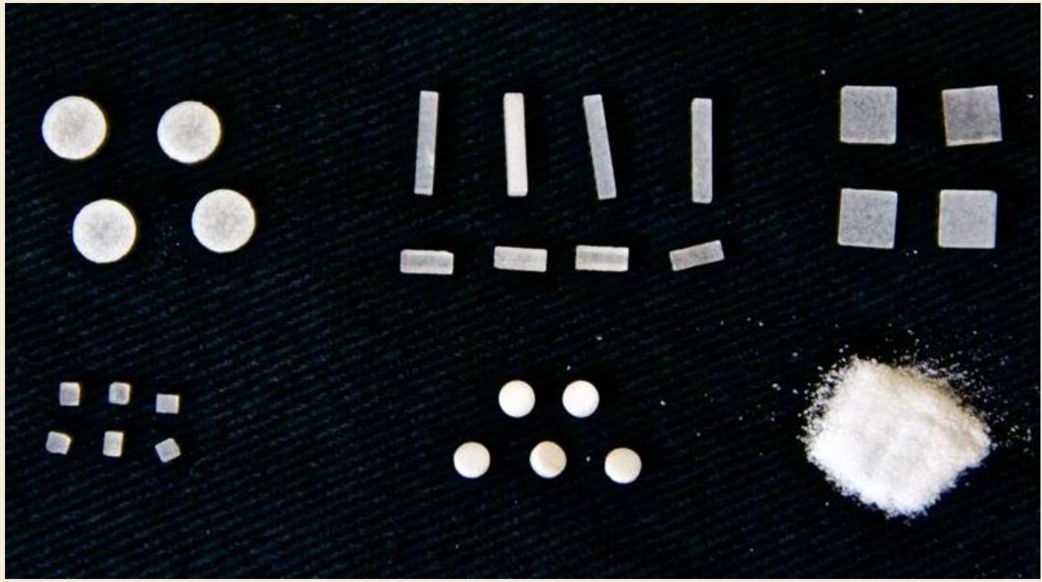
- Keep >40% of audience awake for the entire hour

Outline

1. Introduction
2. Theory
3. Types of LD
4. Factors for dose calculation
5. Batch calibration
6. Practical dose calculation formalisms
7. Commissioning and QA
8. General Handling
9. Safety
10. Reuse
11. Practical Applications
12. Standardization of dose reporting
13. Recommendations

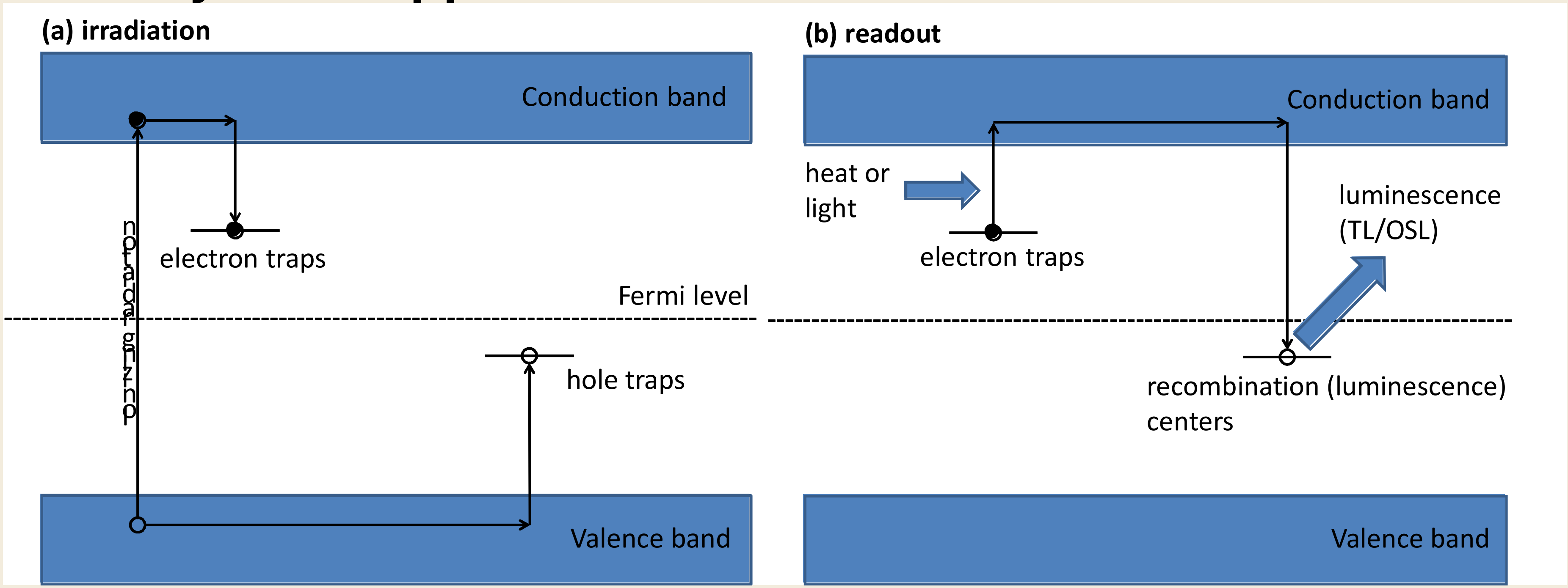
1. Introduction:

- **What is covered?**
  - TLD, OSLD
  - Passive dosimetry
- **What is not covered?**
  - Glass luminescent dosimeters
  - Scintillation dosimeters
  - TLD/OSLD as active dosimeters
- **Most common handling procedures**
  - Most thoroughly vetted in literature
  - Other processes are out there
    - Can be very good, but user beware



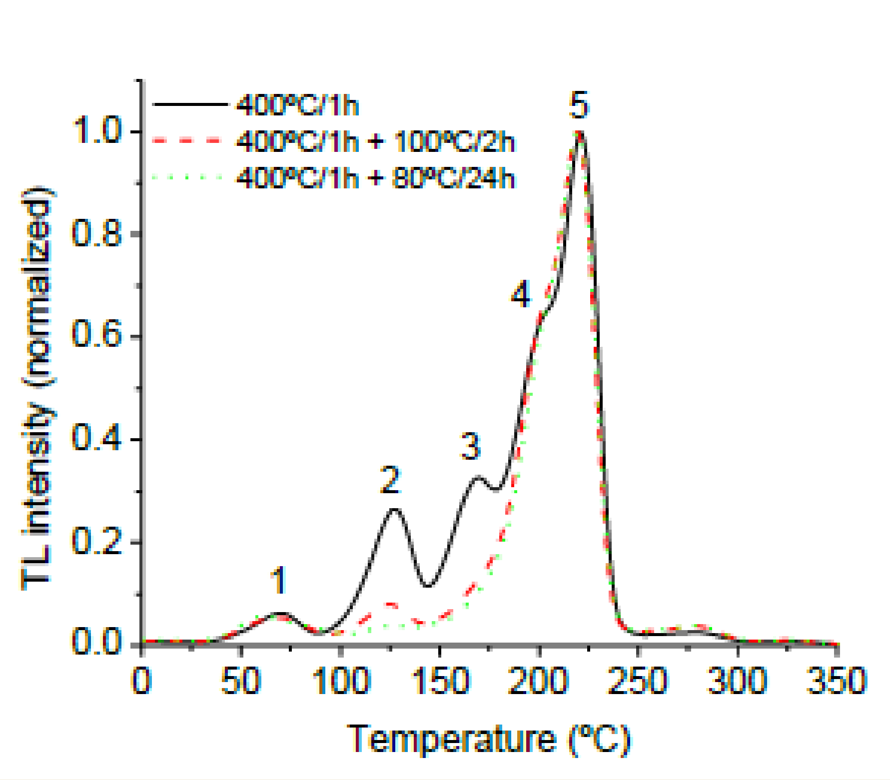
2. Stimulation and Read-out

- **During irradiation, liberated electrons move through crystal lattice and are trapped in energy wells are lattice defects**
- **During readout, trapped electrons are liberated and release light**
  - **TLD: ~all trapped electrons are liberated**
  - **OSLD: very few trapped electrons are liberated**



2. Traps structure

- Traps have many depths
  - Shallow, intermediate, deep
  - TLD: glow curve with many peaks
    - Low T peaks are unstable, remove with a pre-heat cycle
    - Peak 5 is ideal for dosimetry
    - High T peaks are hard to empty without a lot of blackbody noise
  - OSLD: no curve (1s read)
    - Shallow traps are unstable (fading in first 10 minutes)
    - Intermediate traps are good
    - Deep traps are not emptied
      - But serve as competitors for trapping and therefore affect sensitivity and linearity with high accumulated doses.



3. Types of LD

- **There are many types of TLD**
  - Special applications

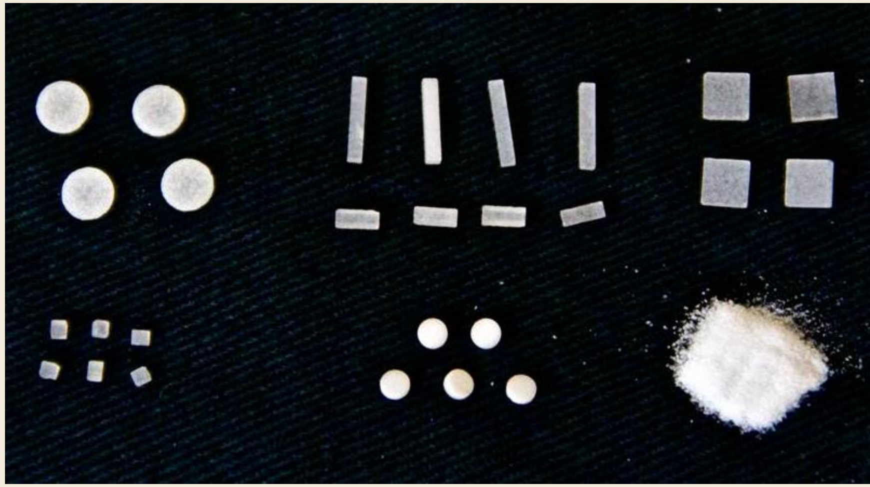
- **Report focuses on:**

  LiF:Ti,Mg (TLD-100)

  Al_2O_3:C (nanoDot)

  - Other Dosimeters discussed
  - May have very different properties

- **TLD available in different presentations**
  - Solid vs. powder



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4. Parameters for calculating dose

D = M * N * Correction factors

$$D_w = M_{corr} \cdot N_{D,w} \cdot k_F \cdot k_L \cdot k_Q \cdot k_\theta$$

- **Mcorr – corrected signal (counts or uC/mg)**
- **N – calibration coefficient (cGy/count)**
- **k_Q – beam quality correction factor**
- **k_L – dose non-linearity correction factor**
- **k_F – fading correction factor**
- **k_θ – angular dependence correction factor**

4. Mcorr – corrected signal (counts or uC/mg)

- Mraw is the raw number of counts or uC/mg
  - OSLD

$$M_{corr} = \frac{\sum_j \left((M_{raw,j} - M_{bkg}) \cdot k_{d,j} \right)}{J}$$

TLD

$$M_{corr} = (M_{raw} - M_{bkg})$$

- Mbkg = background signal
  - Dosimeter with same storage history or same dot (OSLD)
- Read OSLD multiple times (can and should)
  - Signal depletes, but by very small amount (0.05%/reading)
- Typically: $M_{corr} = M_{raw}$

4. Calibration (N)

- We need to relate number of counts to dose
- Irradiate "standards" to a known dose and define N
- Dosimeters irradiated with high precision and control

$$N_{D,w} = \frac{D_0}{\left(M_{0,corr}\right)}$$

- Similar process as for an ion chamber
- N is not traceable to NIST
  - "Standard" is a sort of tertiary standard

4. Calibration (N)

• Ion Chamber

- $D = M\ N\ P_{tp}\ P_{ion}\ k_Q$ ….
- D and M are related by N under calibration conditions
- Calibration conditions more than just 10x10 at 100 cm SSD
  - Full ion collection, STP, Co-60
- The corrections relate the measurement conditions to the calibration conditions – where N is defined and valid
- The calibration conditions are logical
  - STP, full ion collection, reference beam

• LD

- $D = M\ N\ k_L\ k_F\ k_\theta\ k_Q$ ….
- D and M are related by N under calibration conditions
- Calibration conditions include
  - Dose, beam quality, time, orientation
- Corrections also relate measurement conditions to the calibration conditions – where N is defined and valid
- Calibration conditions are less natural
  - What dose? what time after irradiation? What angle of incidence? What beam?

4. Calibration conditions

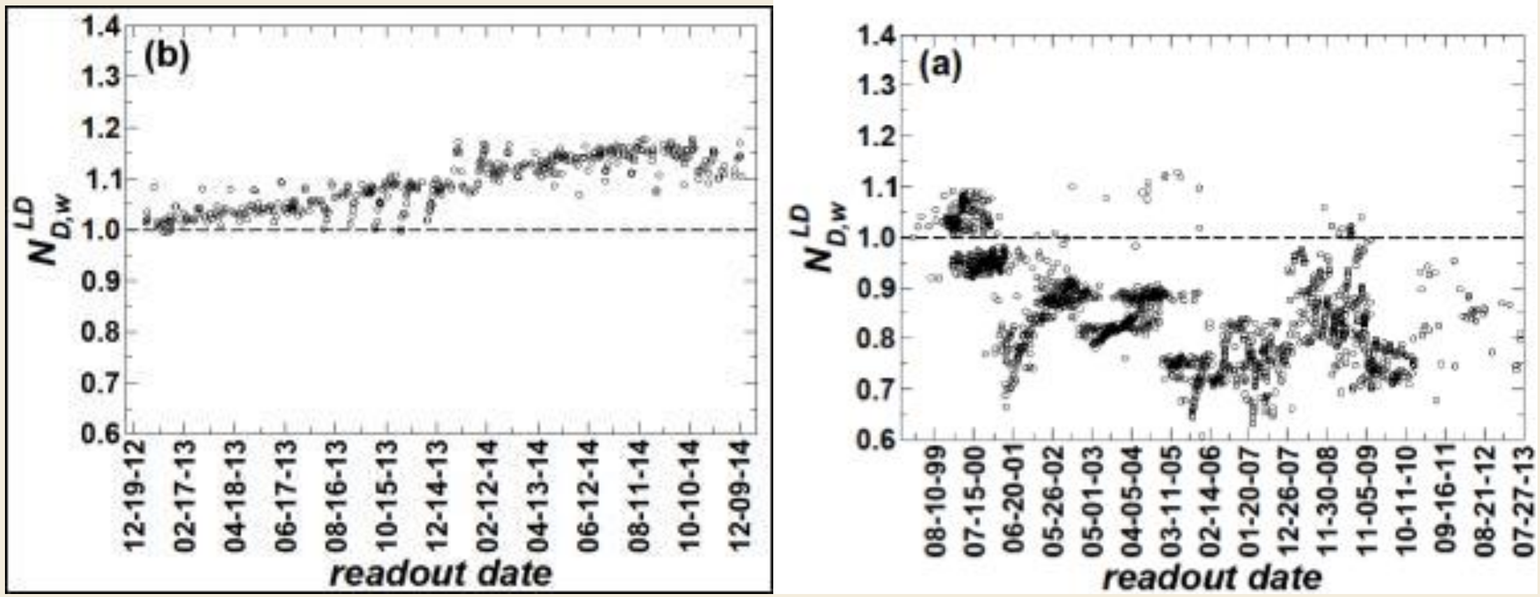
- For ion chamber
  - Logical reference conditions
    - Co-60, STP, full ion collection
- For LD, no natural default
  - Can pick arbitrary calibration conditions
  - Flexible – minimize corrections for given application
  - Requires application of appropriate correction factors to get back to the calibration conditions selected

N = N (dose level, time since irradiation, beam quality, orientation, reader mode, reader……)

4. Calibration options

- For each reading session, irradiate standards appropriate for a given experiment
- Define N for that session
- Best precision, additional work

- Create a calibration curve
  - Provides a one-time N and k_L relationship
- Stability/consistency in N?
- Big differences between readers – can't move
- Variation day-to-day – how to handle?



4. Constancy dosimeter

How to handle the variability in reader output

If you generate a calibration curve, keep an eye on sensitivity:

Irradiate a constancy dosimeter (irradiated to a known dose and corrected for fading a depletion).

1. **Correct for session-specific reader output to determine N (scale output)**
2. **Use N established at the time of the calibration curve – verify no large scale drifts with constancy dosimeter (not reasonable for TLD – too much variability)**

Use common sense with a constancy dosimeter. Reader performance should not change drastically!

4. Corrections

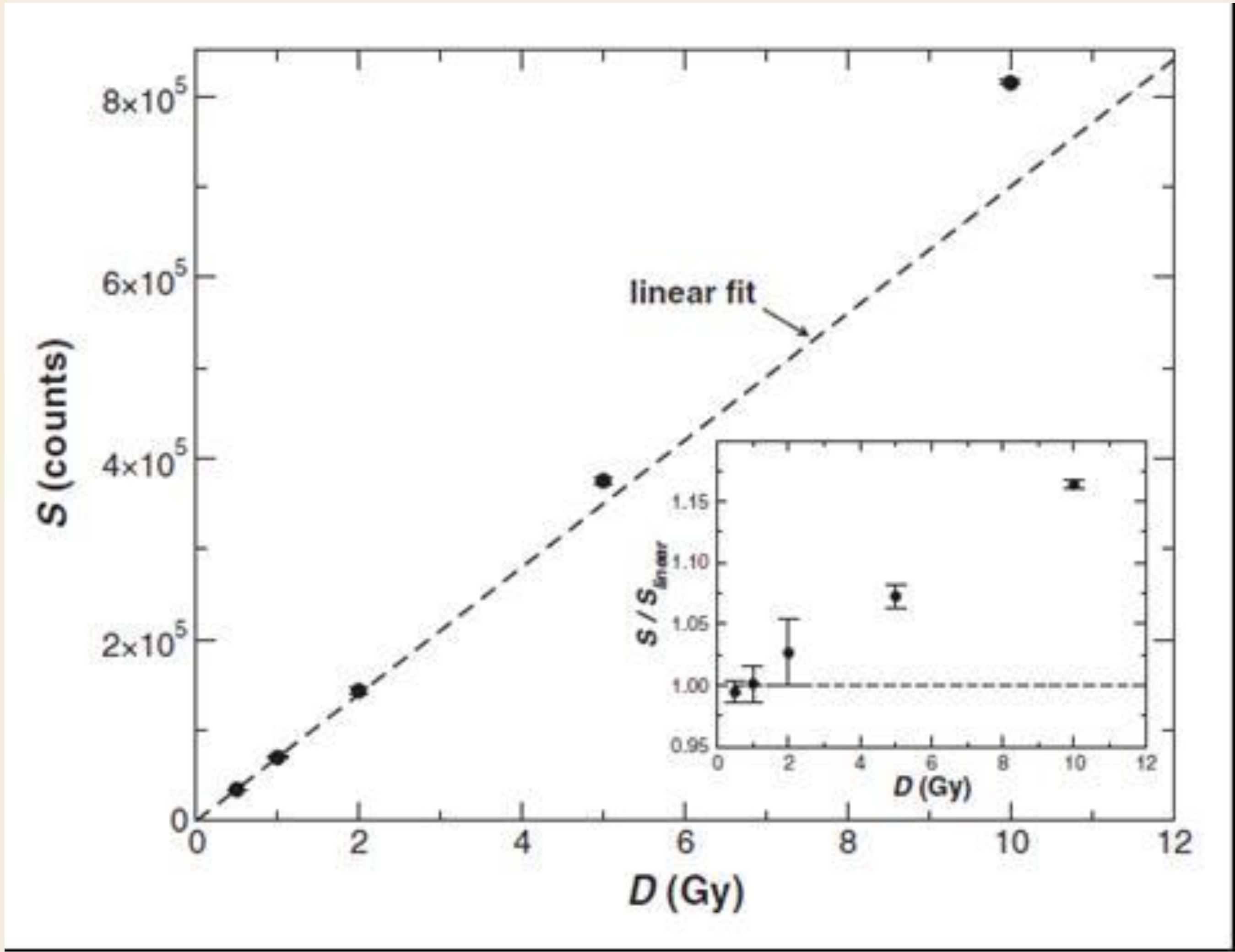
- **We have M and N**
- **If our experimentals and standards are under the same conditions, we are done!**
- **Otherwise, we need to correct for these differences**

- **Linearity, fading, beam quality, angular effects**

4. Linearity k_L

- Response is supralinear at relevant doses
- TLD:
  - Linear up to ~4-5 Gy
- OSLD:
  - Correction is 2-3% at 2 Gy
  - Up to 15% at 10 Gy

- Establish characteristics
- Calibration curve



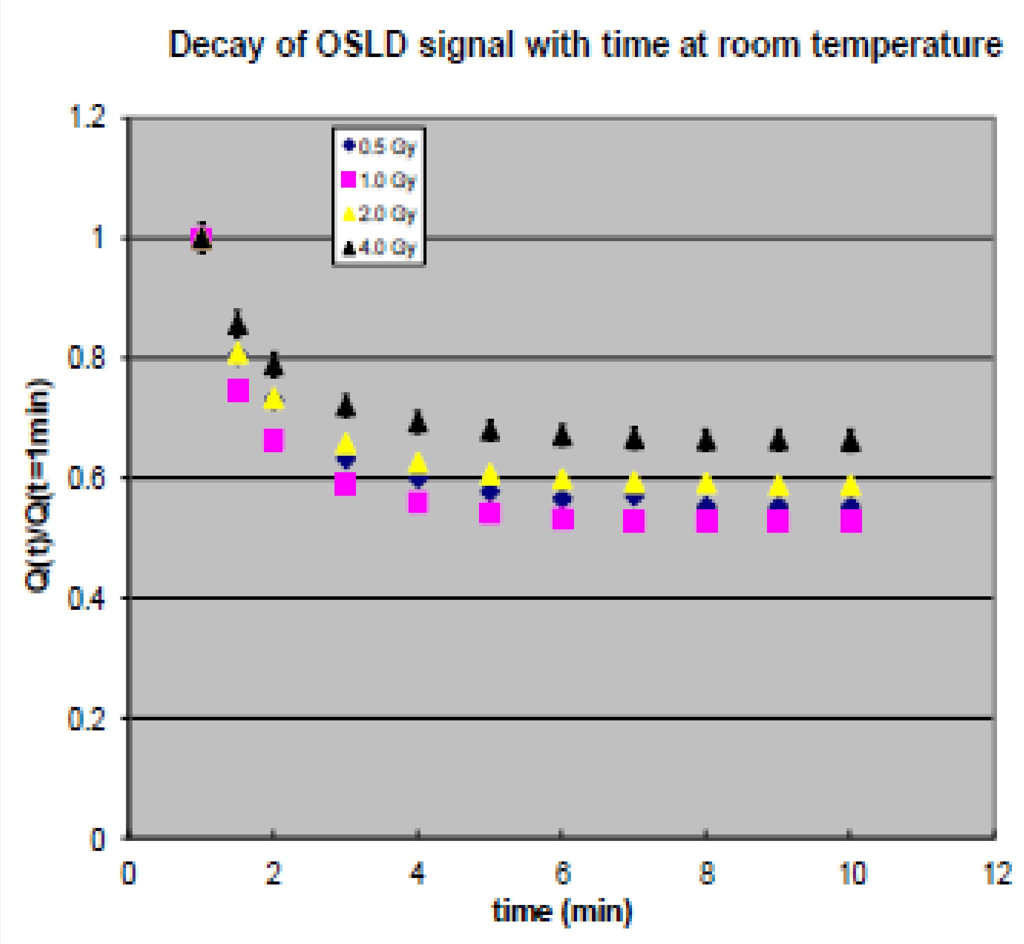
4. Fading k_F

- Spontaneous signal loss with time

- TLD
- Few % in first few days, then 1%/month
  - Even with pre-heating

- OSLD:
- Severe fading in first ~8 minutes
  - Do not read during this time
- After this: 1 % / month

- Account for this issue if a concern
  - High precision, long term record



4. Beam quality k_Q

- **Intrinsic energy dependence:** (change in signal per dose vs energy)
  - Smaller and only for TLD
- **Medium-dependent dependence:** (change in signal compared to water)
  - Predominant issue

- <1% from 6 MV to 18 MV
- Up to 2% between photon and electron (lower)
- Up to 1% (TLD), up to 3% (OSLD) variation as field size and depth change
- Outside the treatment field response can overestimate the dose by 30% or more because of the soft spectrum
- In imaging applications the response can overestimate the dose by a factor of 1.4 for TLD and 3+ for OSLD relative to MV calibration
- Not a concern for many applications, but may need to account for this

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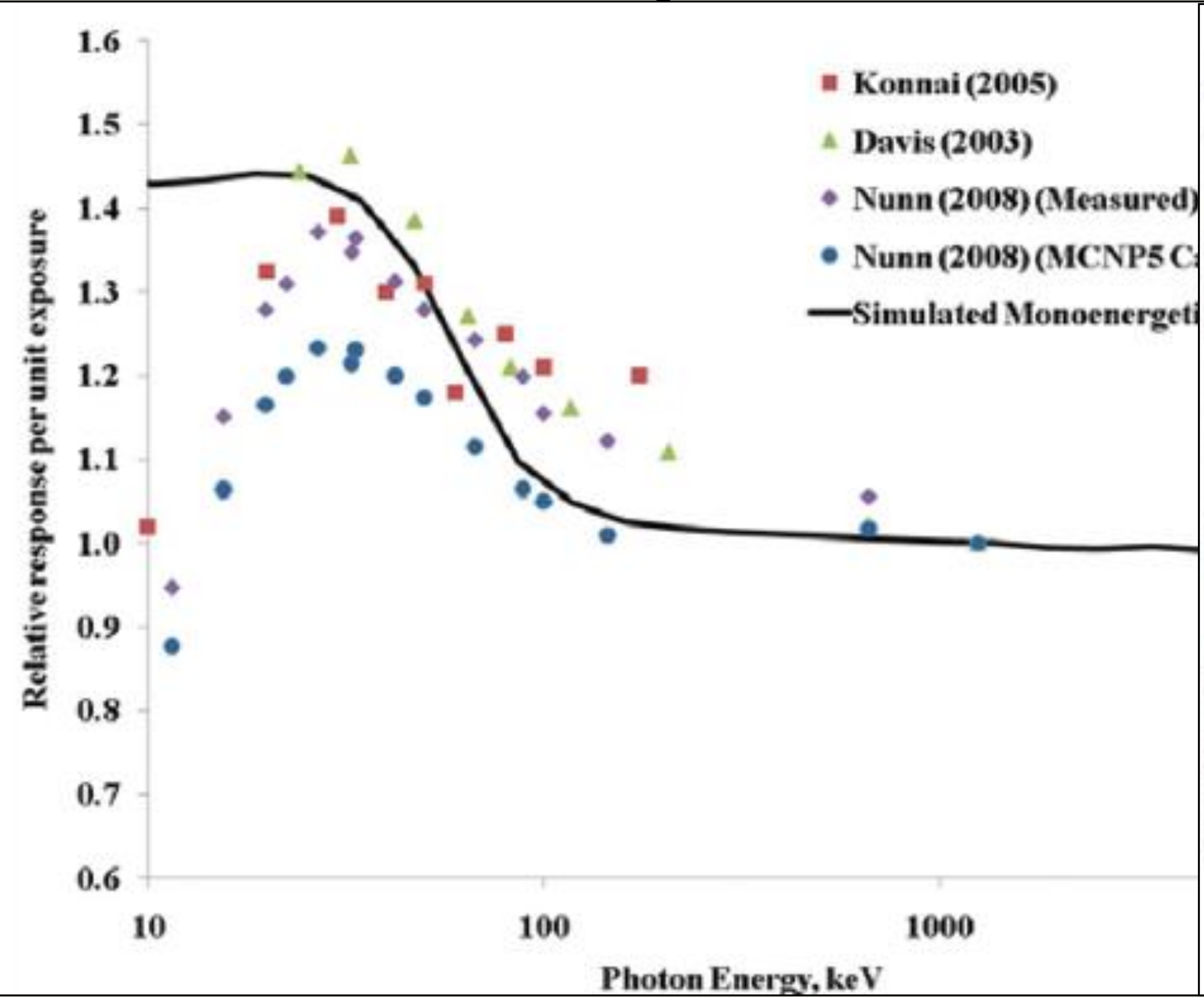
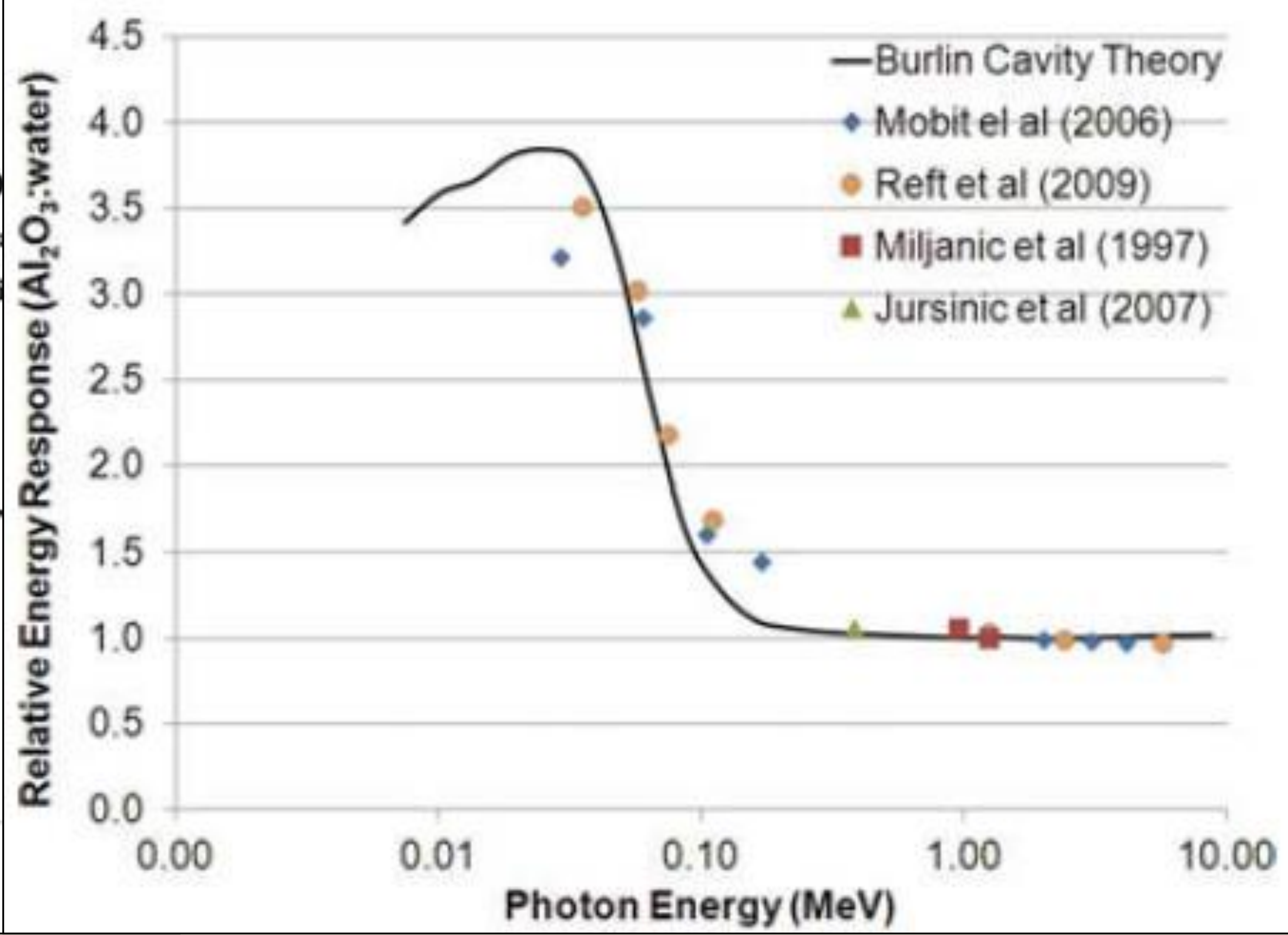
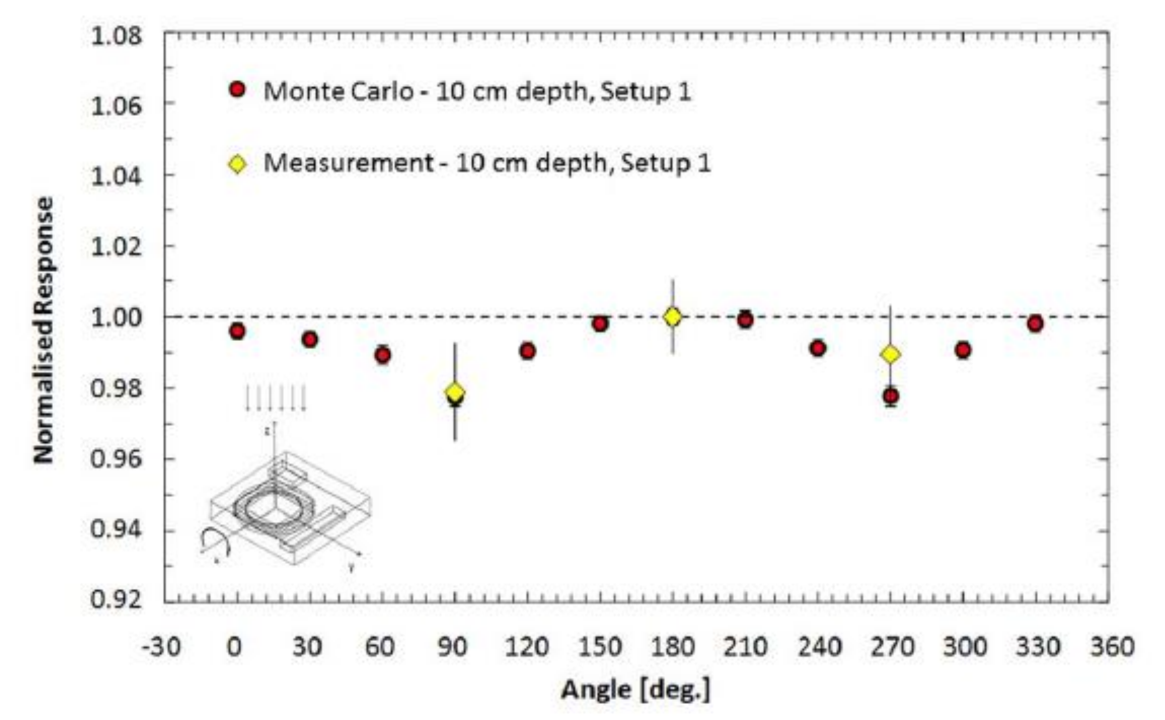
- **Intrinsic energy dependence:** (change in signal per dose vs energy)
  - Smaller and only for TLD

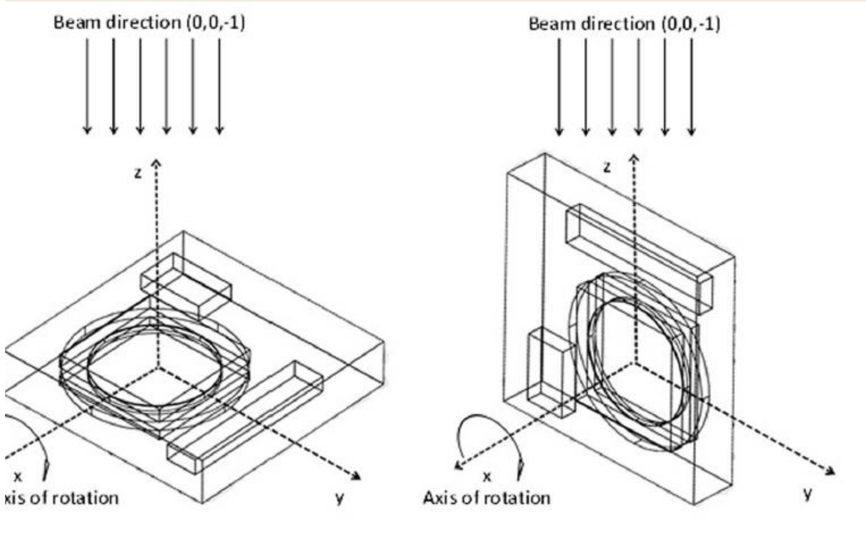




4. Angular dependence k_θ

- **OSLD:**
  - En-face vs edge on
  - 2% difference in a 6X beam, more at lower energy
  - May need to be accounted for
- **TLD:**
  - No angular dependence at MV
  - At low E, with asymmetric presentations, can definitely see





4. Correction factors

- Minimize the magnitude
  - Irradiate standards under similar conditions as experimentals
- Ignore if small (be sure)
  - Increased uncertainty
- Characterize and apply correction factors
  - Increased effort

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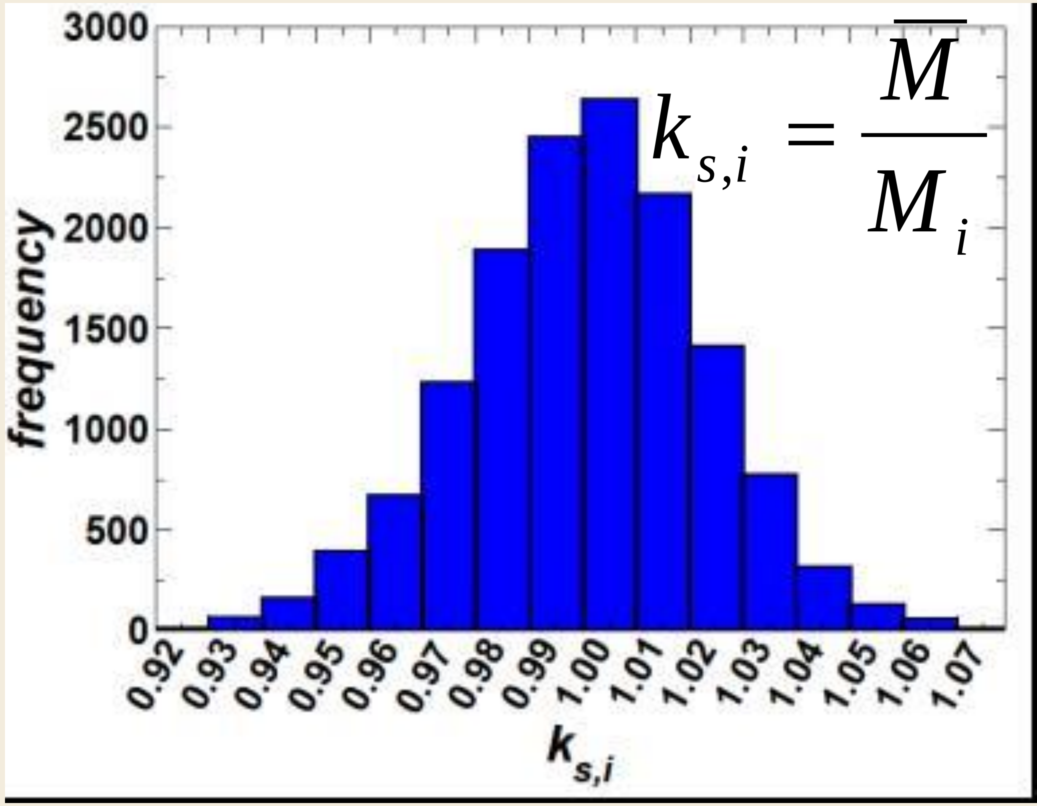
5. Batch calibration

- Assume characteristics are all the same (except sensitivity)
- Sensitivity of dosimeter vs. ave – sensitivity is variable

- Establish $k_{s,i}$ for each dosimeter
  - Irradiate batch of dosimeters to 25cGy
  - Determine relative sensitivity
  - Hard to track, but best precision



$$k_{s,i} = \frac{\overline{M}}{M_i}$$

- Select dosimeters within $k_{s,i}$-window
  - Sensitivity within, say +/- 2%
  - Assume all have equal sensitivity
  - Easy to track, lower precision, discard dosimeters

5. Where does that leave us?

- OSLD

$$M_{corr} = \frac{k_{s,i} \cdot \sum_j \left(\left(M_{raw,j} - M_{bkg} \right) \cdot k_{d,j} \right)}{J}$$

TLD

$$M_{corr} = k_{s,i} \cdot \left(M_{raw} - M_{bkg} \right)$$

- Again, assuming background and depletion are negligible
- Batch calibration:

$$M_{corr} = k_{s,i} \cdot M_{raw}$$

$$D_w = M_{corr} \cdot N_{D,w} \cdot k_F \cdot k_L \cdot k_Q \cdot k_\theta$$

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6. Calibration options

- High precision
  - Establish calibration coefficient for each session – i.e., session specific N
  - Characterize and apply correction factors for all factors (including $k_{s,i}$)
    - Minimized by irradiating standards and experimentals under similar conditions
  - Multiple dosimeters for each reading
- High Efficiency
  - Establish a calibration curve (N and kL together)
  - Verify N is reasonable for the given session
    - TLD: standard
    - OSLD: constancy dot – fading and depletion corrected standard read repeatedly
  - Use a $k_{s,i}$ window
  - Neglect most correction factors (except kL)

6. Calibration options

- Controlled
  - Reference irradiation conditions
  - Experienced handler
- Less Controlled
  - Variable conditions (patient dosimetry)
  - Less experienced handler

6. Uncertainty

	OSLD					TLD			
	High Precision		High Efficiency			High Precision		High Efficiency	
Variable	Controlled	Less Controlled	Controlled	Less Controlled	**Variable**	Controlled	Less Controlled	Controlled	Less Controlled
D_0	0.6	0.6	0.9	0.9	**D_0**	0.6	0.6	0.9	0.9
M_0	0.8	1.6	1.4	2.0	**M_0**	0.7	0.7	1.0	1.4
M_{raw}	0.8	1.6	-	0.8	**M_{raw}**	1.7	1.7	1.7	2.0
k_L	0.3	0.6	0.3	0.6	**k_L**	0.1	0.2	0.1	0.2
k_F	0.1	0.2	1.0	2.0	**k_F**	0.7	1.4	1.0	2.0
k_Q	0.9	2.9	1.0	3.0	**k_Q**	1.1	2.0	1.0	2.0
$K_{s,i}$	-	-	2.8	2.8	**$K_{s,i}$**	0.0	2.0	2.5	2.5
K_θ	0.0	1.0	0.0	1.0	**K_θ**	0.0	0.0	0.0	0.0
Total (1-sigma)	1.6	3.9	3.5	5.2	**Total (1-sigma)**	2.3	3.7	3.6	4.6
Total (2-sigma)	**3.2**	**7.9**	**7.0**	**10.5**	**Total (2-sigma)**	**4.7**	**7.4**	**7.2**	**9.1**

6. Calibration options

- This uncertainty is uncertainty in the dosimeter

- Placement on a patient (particularly by a therapist) can add additional (substantial uncertainty) positioning error
- Comparison with TPS has additional TPS error

- Large scale in vivo program showed agreement with TPS >10% (1-sigma)

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7. Commissioning and QA

- Table for commissioning of:
  - –TLD/OSLD dosimeter
  - –TLD/OSLD reader
- Table for QA
  - –Per session
  - –Per year
- Divided up based on high precision or high efficiency

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8. General Handling

- TLD
  - Placement of TLD/distribution of powder makes a difference (1-3%)
  - Amount of powder makes a difference (too little or too much)
  - Can mark chips (graphite pencil on edges)

- OSLD
  - You can immerse in water for a reasonable period of time
  - If detector pops open, don’t lose a lot of signal
  - Warm up reader before use (or leave it on continuously)
  - Operator can influence precision
    - Knob turning is a skill! 1-2% extra uncertainty for novice operators

9. Safety

Material	Health		Fire		Reactivity		Physical
	NFPA	HMIS	NFPA	HMIS	NFPA	HMIS	HMIS
LiF	1	1	0	0	0	0	*
Al_2O_3	0	0	0	0	1	*	1

* None listed

Note: NFPA ratings are on scale of 0-4, with 0 being no hazard and 4 being extreme hazard.

- Don't eat them
- Don't rub your eyes with them
- Don't smoke them
- Don't freebase them
- Don't inject between your toes

- Do wash your hands after handling
- Do follow good lab practice
  - No food or drink

10. Reuse

- TLD (24 hour heating regimen, well defined)
  - Can reuse indefinitely with consistent anneal
  - Sensitivity is highly affected by annealing
  - Anneal as a group
- OSLD: (expose to light for ~24 hours)
  - Bleaching does not empty deep traps!
  - This affects relative trapping and recombination efficiency
    - Changes sensitivity!
    - Changes supralinearity!
  - Relationship is complicated
    - Depends on bleaching regimen = messy
- Do not use past 10 Gy

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11. Photon beam applications

- Primary beam dosimetry
  - Generally use bolus over dosimeter to avoid high gradient
- Skin/surface dosimetry
  - Dosimeters don't measure at surface, overestimate by 10-40+%
- Small field dosimetry
  - Must use small presentations.
    - OSLD disc is too large
    - 3mm capsules unreliable below 12.5 mm
    - TLD microcubes can go down to 6 mm x 6 mm
  - Accuracy good within 2% compared to other dosimeters to at least 10 mm field size, larger errors below this

11. Other applications

- Electron beam dosimetry
  - Don’t use OSLD for fields smaller than 2 cm x 2 cm
  - Energy dependence is minimal, angular dependence has not been evaluated
- Proton beam dosimetry
  - Signal/dose is less for high LET.
    - E.g., k_Q is 1.05 for OSLD in protons
  - Consistent across LET for protons, but not for carbon

11. Other applications

- Brachytherapy and kV applications
  - Energy dependence becomes a larger correction
    - Also more sensitive to variations in spectrum (particularly OSLD)
    - E.g., for CT, k_Q depends on kV (10-15%), filter (10%), and scan extent (5%)
  - Angular dependence becomes a larger concern (particularly OSLD)
  - Linearity is less of a concern
  - Reproducibility of LDs is still good down to very low doses
    - 5 mGy

11. Other applications

- Out of field applications
- Energy is lower, dosimeter overresponds
  - 5-12% correction for TLD, 10-25% for OSLD
- Place bolus over dosimeter (to nominal ~ dmax)
  - Scattered electron dose at patient surface – dose elevated at surface outside the treatment field, don't generally want to measure this.
  - Factor of 2-5
- Watch out for TLD-100, overresponds to neutrons (10X)
  - Don't measure outside the treatment field for 15 or 18 MV
  - Use OSLD of TLD-700

11. Other applications

- Measurement of neutrons
- Intraoperative therapy
- Cell and blood irradiators

- See report for details.

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12. Standardization of dose reporting

- **When reporting an LD process (or considering it), include:**

- **Material** (name, form, dimensions, selection methodology)
- **Readout process** (Reader type, corrections, # readings)
- **Calibration methodology** (Nature of standards)
- **Uncertainty estimate** (typical reproducibility and overall uncertainty)

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13. Recommendations (General)

- Whenever starting to use a new dosimeter, a series of phantom and in vivo measurements comparing the old and new dosimeters should be performed. The precision should be similar to that predicted by Section 6.
- Define a calibration and readout process (examples are provided in section 6) that meets clinical needs based on workflow and acceptable uncertainty.
- Review and apply the commissioning and ongoing QA protocols (Section 7).
- Know the uncertainties associated with your chosen approach (Section 6).
- Handle LDs with care to avoid damage (Section 8).
- Use LDs (including annealing/bleaching, storage, handling, etc.) in a consistent manner to maximize reproducibility.

13. Recommendations (Dose Calculation)

- **Readout Reproducibility**. Do at least three readouts for each OSLD.
- **System Calibration Coefficient ($N_{D,W}$)**. TLD: calibration coefficient must be determined for every reading session. OSLD: determined for each session or calibration curve.
- **Linearity (k_L)**. Necessary to account for unless at low dose (via a correction factor or calibration curve). Minimized by irradiating standards and experimental to the same dose.
- **Beam quality, angular sensitivity (k_Q, k_θ)** Accounted for if precision warrants (via a correction factor). Minimized by irradiating standards and experimentals under same conditions.
- **Fading (k_F)**. Wait at least 10 min for OSLDs and at least 12 h for TLDs.
- **Element Sensitivity ($k_{s,i}$)** (solid LDs only). The user may determine an acceptability window or track the relative sensitivity of each LD if batch calibration is used.

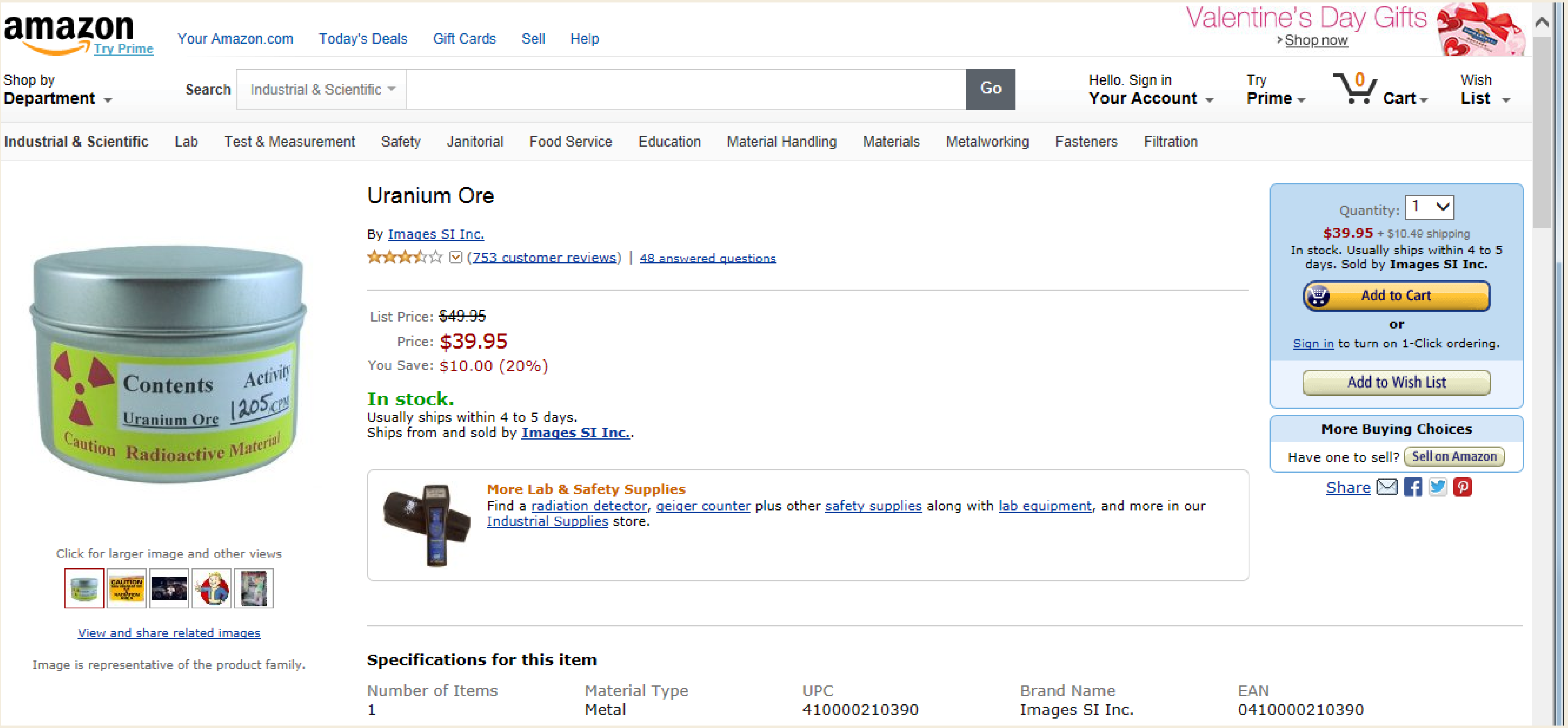
13. Recommendations (Reuse)

- If a consistent annealing procedure is used, TLDs may be re-used indefinitely.
- All individual TLDs from a batch should be annealed as a group to maintain their common properties.
- nanoDot OSLDs should be used only up to a cumulative dose of 10 Gy. Use to higher doses introduce many complications including changing in sensitivity, linearity, and background signal that are dependent on the bleaching history.

13. Recommendations (Special Use)

- For brachytherapy applications, special attention should be paid to dose gradients and to the beam quality correction factor; angular dependence may also require attention (Section 11.4).
- For imaging applications, calibration and energy correction factors require particular attention, as may angular dependence. Additionally, the background signal may need to be monitored (Section 11.5).
- For out-of-field measurements of photons >10 MV, select an LD that is neutron insensitive to avoid detector over-response to neutron contamination (Section 11.6).
- Secondary neutron dosimetry with LD must be performed with the full understanding of the energy response of the detector. LDs only respond meaningfully to thermal neutrons (Section 11.7).

Thank You!



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