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Establishing MOSFET-Based In-Vivo Dosimetry in Radiotherapy Practice

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- MOSFET Calibration
- Integration into clinical practice
- Summary

Introduction – In-vivo dosimetry in Radiotherapy

- In vivo dosimetry is an essential quality assurance method in radiation therapy for evaluating the difference between prescribed and delivered dose
- Common applications include total body irradiation (TBI, ~150–200 cGy), skin dose verification, and dose assessment for cardiac devices (as low as a few cGy)
- Common dosimeters include OSLDs, TLDs, diodes, and films
- In general, 10% total uncertainty is accepted for in-vivo dose measurements

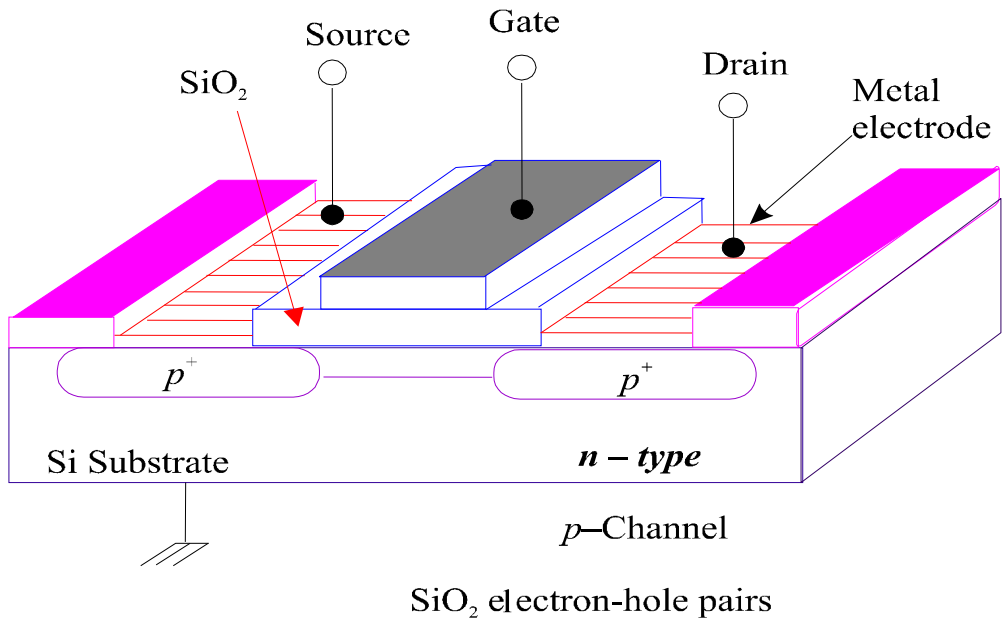
Figure 1. Set up of TBI treatment. https://radiologykey.com/total-body-irradiation-2/

Introduction - the Principles of MOSFET

- Metal oxide semiconductor field effect transistors (MOSFETs) are considered as a favorable solution for in-vivo dosimetry because of its:
  - Relatively independent response to radiotherapeutic energies and dose rate
  - Negligible attenuation of the radiation
  - Portability and small size
  - Real-time reading

Introduction - the Principles of MOSFET

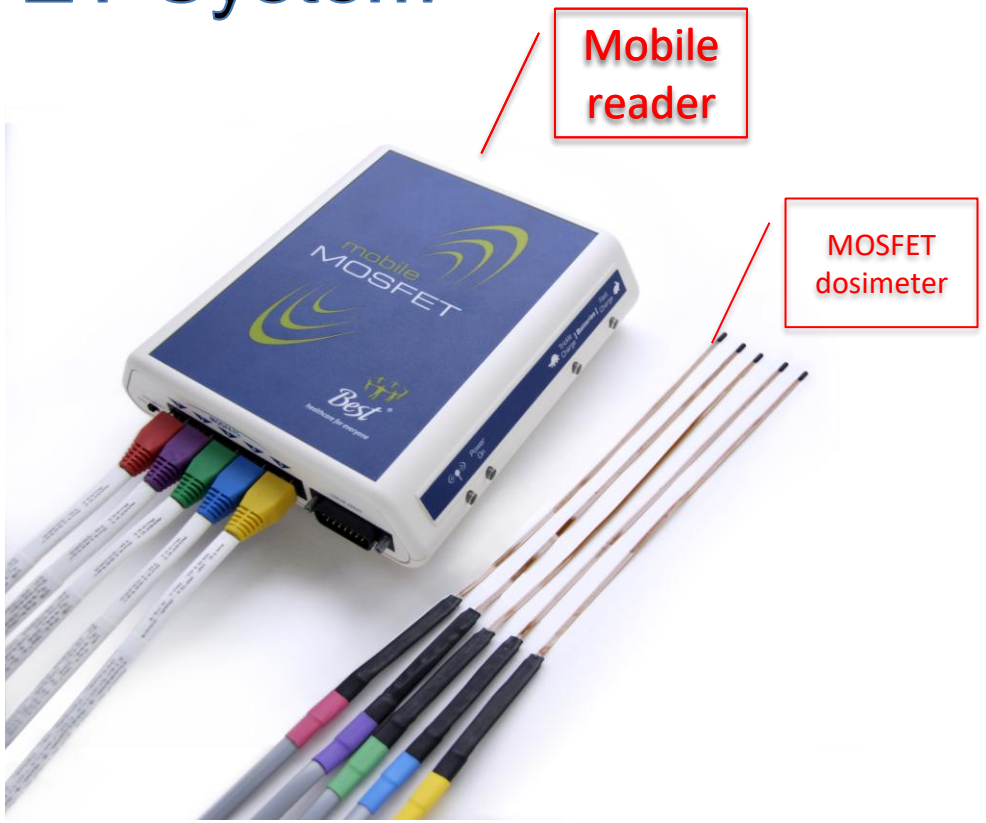
- Principles:
  - Radiation creates electron-hole pairs in SiO2
  - With a bias voltage applied, the electrons migrate out of the oxide, while holes are trapped at the interface
  - The accumulation of these trapped charges changes the amount of voltage required to turn the transistor on, i.e. ΔV_{th}
  - Change in ΔV_{th} is proportional to the change in number of trapped holes and thus, to absorbed dose.

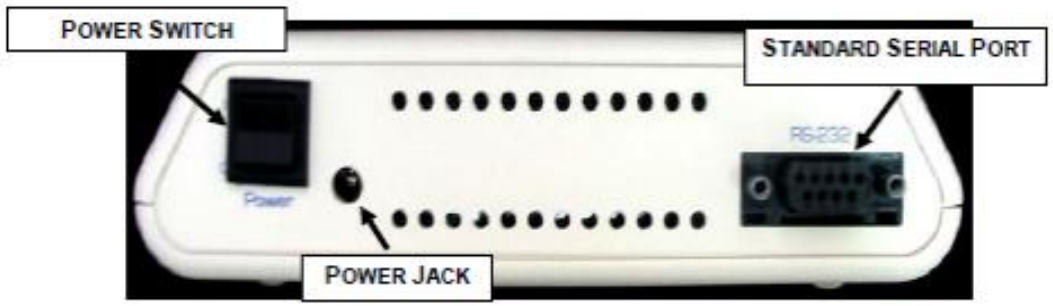


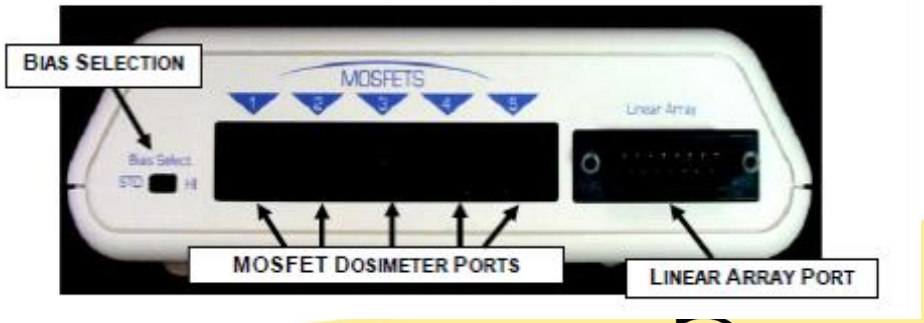
ΔV_{th} ~ radiation dose

Introduction - Mobile MOSFET System

- Mobile MOSFET System (Best Medical, Inc.)
  - Portable; Bluetooth wireless
  - 1 reader hosts up to 5 dosimeters
  - Battery operated – up to 20hrs after being fully charged
    - Based on experience, battery only lasts for about 6-7 hours
  - Two configure bias sensitivity
    - STD (standard sensitivity mode): TBI/central dose
    - HI (high sensitivity mode)







Introduction - Mobile MOSFET System

- MOSFET dosimeters (Model TN-502RD-H)
  - Standard Sensitivity with Heat Shrink Reinforcement
  - 0.2 * 0.2 mm active area; 1.4 m cable
  - Temperature independent
  - Inherently prone to radiation damage (life span ~100Gy)
  - Dose range: 200Gy for standard sensitivity bias, 70Gy for high sensitivity bias
  - Fading: <3% of 200 cGy when read within 15 min of exposure
  - Frequent calibrations not necessary
  - Nominal sensitivities

STANDARD SENSITIVITY DOSIMETER MODELS TN-502RD & TN-502RDM

DOSIMETER	BIAS SENSITIVITY SETTING	NOMINAL SENSITIVITY	ENERGY SOURCE
Standard	Standard	1 mV/ cGy	Co^{60} with buildup
Standard	High	3 mV/ cGy	Co^{60} with buildup
Standard	Standard	3 mV/ R	Diagnostic X-ray
Standard	High	9 mV/ R	Diagnostic X-ray

Purpose

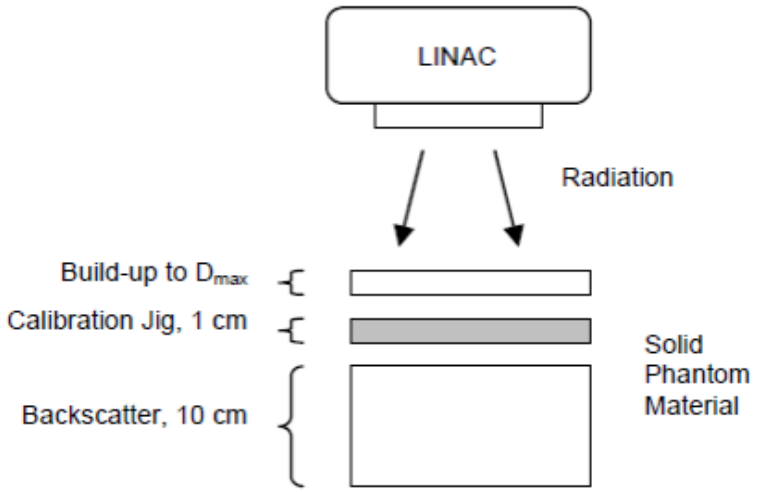
- Determine the calibration coefficient and overall measurement uncertainty of the MOSFET detector to evaluate its suitability for in-vivo dosimetry.
- Establish a clinical workflow for implementing MOSFET-based in-vivo dosimetry in radiation oncology

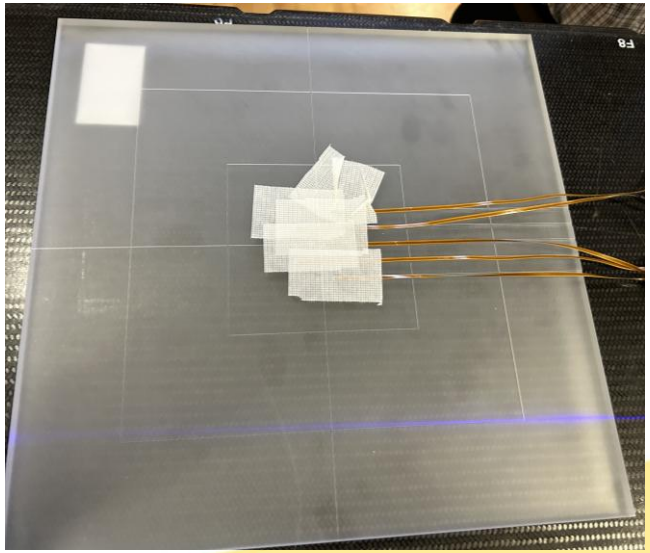
MOSFET Calibration

- Calibration coefficient (mV/cGy)

$$CF(Q) = \frac{\Delta V_{th}}{D_0(Q)}$$

  - $D_0(Q)$ (cGy): radiation dose measured under reference condition with beam quality Q
  - ΔV_{th} (mV): change of threshold voltage
- $D_0(Q)$ measurement
  - Ion chamber: calibration can be traced back to NIST
  - Reference conditions:
    - Photon: 100 cm SAD, 10 x 10 cm field size, 200 MU, 1.5cm depth for 6MV, 2.8cm depth for 15MV
    - Electron: 100 cm SSD, 15 x 15 cone, 200 MU, Dmax for each energy
- ΔV_{th} recorded before and after each trial





Calibration jig provided by *Best Medical*: 30 x 30 x 1 cm, PMMA

MOSFET Calibration – dosimeter characteristics

- Reproducibility

Beam quality	6MV photon	15MV photon	6FFF photon	9MeV electron
cGy/MU	0.99825	1.00323	1.00042	0.99121
Delivered MU	200	200	50	50
Delivered dose (cGy)	199.65	200.646	50.021	49.5605

	6MV				15MV				6FFF				9MeV			
MOSFET #	CF1	CF2	CF3	STD/AVG	CF1	CF2	CF3	STD/AVG	CF1	CF2	CF3	STD/AVG	CF1	CF2	CF3	STD/AVG
1	1.07	1.08	1.08	0.32%	1.04	1.06	1.04	0.90%	1.01	0.99	1.01	0.94%	1.06	1.04	1.02	1.57%
2	1.07	1.03	1.08	1.93%	1.07	1.05	1.06	0.77%	1.03	1.02	1.01	0.80%	1.03	1.03	1.06	1.36%
3	1.05	1.06	1.05	0.63%	1.05	1.04	1.04	0.45%	1.06	1.05	1.02	1.63%	1.02	1.09	1.1	3.33%
4	1.04	1.07	1.07	1.15%	1.07	1.05	1.07	0.89%	1.04	1.02	1.03	0.79%	1.05	1.04	1.01	1.64%
5	1.04	1.06	1.08	1.35%	1.08	1.06	1.07	0.76%	1.09	1.06	1.04	1.93%	1.08	1.06	1.08	0.88%

- Single dosimeter reading reproducibility: up to **~2% for photon beams** and **~3.5% for electron beams**
- Inter-dosimeter CF difference: **~3% for photon beams** and up to **~ 5% for electron beams**

MOSFET Calibration – dosimeter characteristics

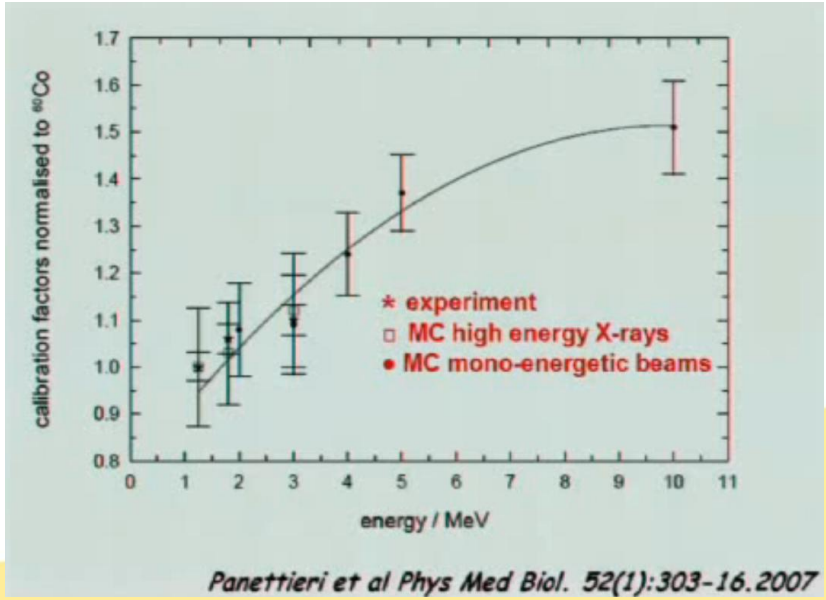
- Energy Dependence – photon

	6MV				15MV				6FFF			
MOSFET #	**CF1**	**CF2**	**CF3**	**AVG**	**CF1**	**CF2**	**CF3**	**AVG**	**CF1**	**CF2**	**CF3**	**AVG**
1	1.07	1.08	1.08	**1.08**	1.04	1.06	1.04	**1.04**	1.01	0.99	1.01	**1.00**
2	1.07	1.03	1.08	**1.06**	1.07	1.05	1.06	**1.04**	1.03	1.02	1.01	**1.02**
3	1.05	1.06	1.05	**1.05**	1.05	1.04	1.04	**1.07**	1.06	1.05	1.02	**1.04**
4	1.04	1.07	1.07	**1.06**	1.07	1.05	1.07	**1.03**	1.04	1.02	1.03	**1.03**
5	1.04	1.06	1.08	**1.06**	1.08	1.06	1.07	**1.07**	1.09	1.06	1.04	**1.06**

- Energy Dependence – electron

MOSFET #	**CF-6E**	**CF-9E**	**CF-12E**	**CF-16E**	**CF-20E**	**Avg**	**STD/AVG**
1	0.99	1.00	1.04	0.99	1.04	**1.02**	**2.50%**
2	1.00	1.03	1.03	1.02	1.02	**1.02**	**0.77%**
3	1.03	1.04	1.00	1.07	1.00	**1.02**	**3.20%**
4	1.02	1.06	1.00	1.03	1.00	**1.01**	**1.26%**
5	1.05	1.07	1.07	1.03	1.02	**1.04**	**2.21%**

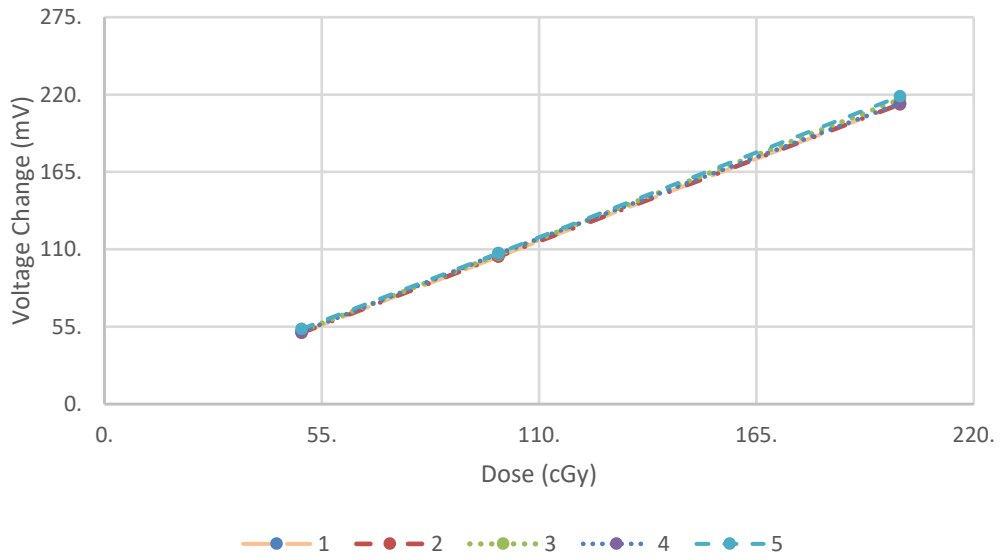
- With a limited number of measurements and dosimeters, the contributions of reproducibility and inter-dosimeter variability cannot be excluded. **The combined effect remained within 3.5%.**



MOSFET Calibration – dosimeter characteristics

- Linearity: with example of 6MV photon beams

	Voltage Change (mV)							
MOSFET #	**49.885 (cGy)**	**99.68 (cGy)**	**201.36 (cGy)**	**CF1**	**CF2**	**CF3**	**Avg CF**	**Std CF/Avg CF**
1	50.62	104.74	213.1975	1.0147	1.0508	1.0588	1.0414	1.84%
2	54.93	106.84	214.13	1.1011	1.0718	1.0634	1.0788	1.50%
3	51.91	106.27	216.61	1.0406	1.0661	1.0757	1.0608	1.40%
4	51.27	106.89	213.7	1.0278	1.0723	1.0613	1.0538	1.80%
5	53.38	107.27	218.79	1.0701	1.0761	1.0866	1.0776	0.63%



- **The linearity is within 2%**

MOSFET Calibration – dosimeter characteristics

- Low dose performance
  - Standard sensitivity bias – 6MV

	Vtg change (mV)					CF (mV/cGy)						
MOSFET #	20MU	10MU	5MU	2MU	1MU	20MU	10MU	5MU	2MU	1MU	AVG	STD/AVG
1	23.38	11.44	4.58	1.48	1.57	1.17	1.15	0.92	0.74	1.57	**1.11**	**25.23%**
2	19.71	10.04	5.45	2.14	0.9	0.99	1.01	1.09	1.07	0.90	**1.01**	**6.68%**
3	21.63	10.31	5.73	1.4	1.12	1.08	1.03	1.15	0.70	1.12	**1.02**	**16.00%**
4	23.14	10.31	4.31	1.44	0.83	1.16	1.03	0.86	0.72	0.83	**0.92**	**16.84%**
5	22.18	11.55	5.91	2	0.85	1.11	1.16	1.18	1.00	0.85	**1.06**	**11.49%**

  - High sensitivity bias – 6MV

	Vtg change (mV)					CF (mV/cGy)						
MOSFET #	20MU	10MU	5MU	2MU	1MU	20MU	10MU	5MU	2MU	1MU	AVG	STD/AVG
1	73.04	35.8	18.84	6.99	3.23	3.66	3.59	3.77	3.50	3.24	**3.55**	**5.11%**
2	73.05	36.25	18.71	7.06	3.43	3.66	3.63	3.75	3.54	3.44	**3.60**	**2.98%**
3	71.37	36.91	17.13	7.49	3.87	3.57	3.70	3.43	3.75	3.88	**3.67**	**4.15%**
4	72.48	36.85	17.62	6.48	3.91	3.63	3.69	3.53	3.25	3.92	**3.60**	**6.08%**
5	71.58	37.43	17.13	6.98	3.28	3.66	3.59	3.77	3.50	3.24	**3.51**	**4.41%**

MOSFET Calibration – dosimeter characteristics

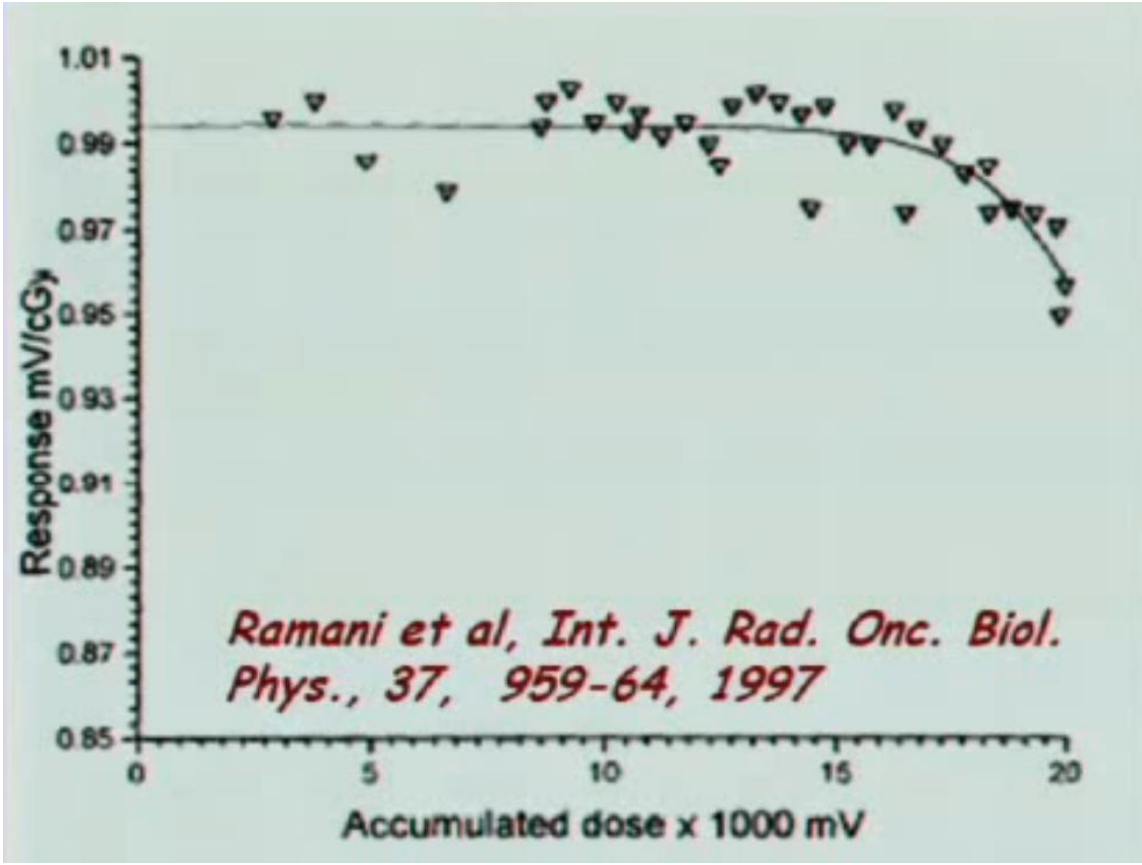
- Low dose performance
  - High sensitivity bias – 15MV

	Vtg change (mV)					CF (mV/cGy)						
MOSFET #	20MU	10MU	5MU	2MU	1MU	20MU	10MU	5MU	2MU	1MU	Avg	Std/Avg
1	72.86	36.08	18.86	7.53	3.58	3.63	3.60	3.76	3.75	3.57	3.66	2.18%
2	71.67	35.52	18.87	6.35	3.84	3.57	3.54	3.76	3.16	3.83	3.57	6.48%
3	72.81	35.98	18.38	6.88	3.42	3.63	3.59	3.66	3.43	3.41	3.54	2.96%
4	72.32	36.11	17.69	7.44	3.87	3.60	3.60	3.53	3.71	3.86	3.66	3.14%
5	72.05	35.08	18.59	7.22	3.54	3.59	3.50	3.71	3.60	3.53	3.58	2.01%

- High sensitivity mode should be used for low dose (<20cGy)
- Measurement error for low dose measurement is up to 6.5%

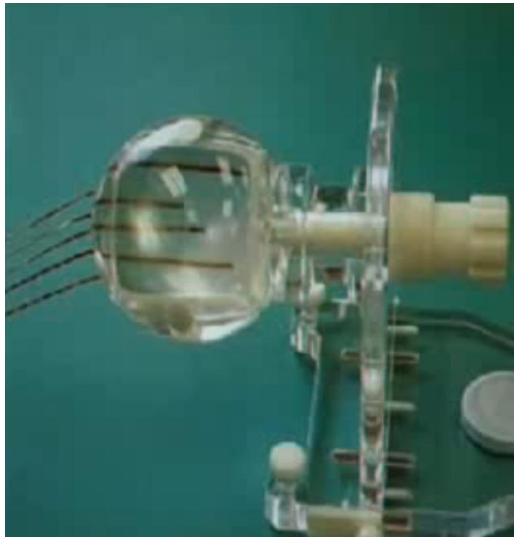
MOSFET Calibration – dosimeter characteristics

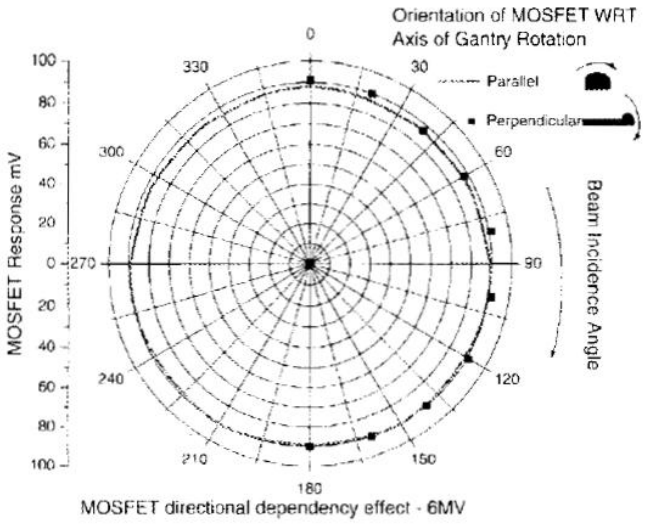
- Effect of accumulated dose
  - Response degrades around accumulated voltage change of 17500 mV



MOSFET Calibration – dosimeter characteristics

- Angular dependence
  - Angular dependence has been reported in multiple studies.
  - For MV photons, the reported angular dependence is typically about ±2% to ±3% under controlled in-phantom or build-up conditions, but can increase to ~17%–68% at surface or oblique-incidence conditions.
  - An isotropic phantom should be used to evaluate angular dependence
  - For TBI measurements, angular dependence is less a concern





MOSFET directional dependency effect - 6MV

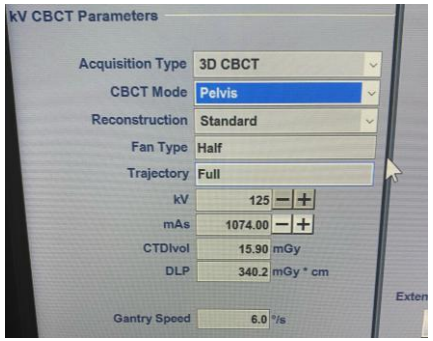
±2.5% from Best Medical, Inc

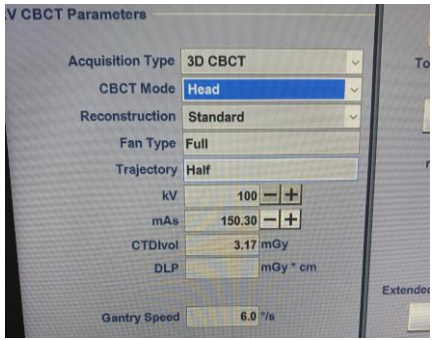
Paper	Beam Quality	Setup / geometry	Angular dependence
Kumar et al., 2014	Co-60, 6 MV, 15 MV	Mobile MOSFET; gantry-angle study with and without brass build-up cap	With build-up cap: about ±2%. Without build-up: up to ~6% (Co-60), 25% (6 MV), 60% (15 MV), with maxima at 90° and 270°
Qin et al., 2014	MV photons, **surface dose**	MOSFET on top surface of solid-water phantom; oblique beam incidence	MOSFET20: max 16.9% at 72°. OneDose: max 21.7% at 59°. OneDosePlus: max 68.4% at 90°
Gopiraj et al., 2008	6 MV photons	MOSFET at isocenter in cylindrical phantom; gantry angles from ±45°	Response varied within ±3%
Petoukhova et al., 2017	Electron IORT	MOSFET / film in vivo dosimetry for APBI	Angular dependence reported as within 3%

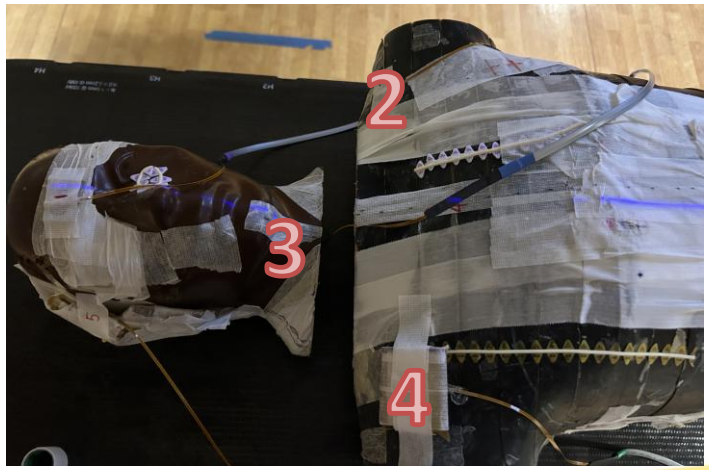
MOSFET Calibration – dosimeter characteristics

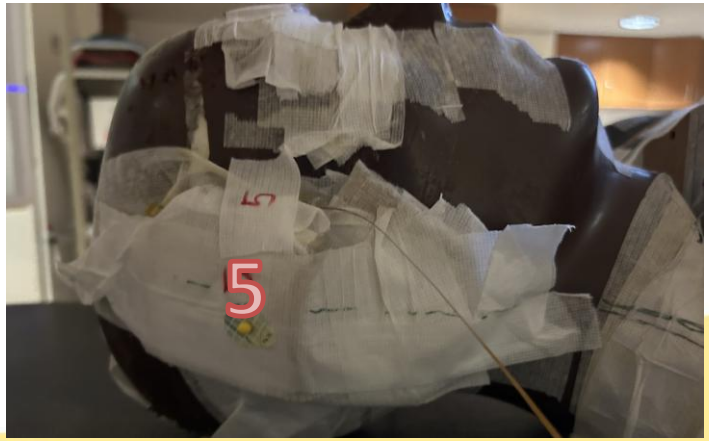
- KV energy Response

			STD mode Dose (cGy)		High sensitivity mode Dose (cGy)	
MOSFET #	**Location**	**Bolus**	**KV CBCT (head)**	**KV CBCT (pelvis)**	**KV CBCT (head)**	**KV CBCT (pelvis)**
1	forehead	No	0.46	2.18	0.10	0.88
2	L shoulder	No	0.34	0.84	0.09	1.58
3	near iso	No	1.13	19.96	1.25	17.47
4	R shoulder	Yes	0.66	1.64	0.29	1.01
5	R skull	Yes	0.60	3.10	0.25	2.26









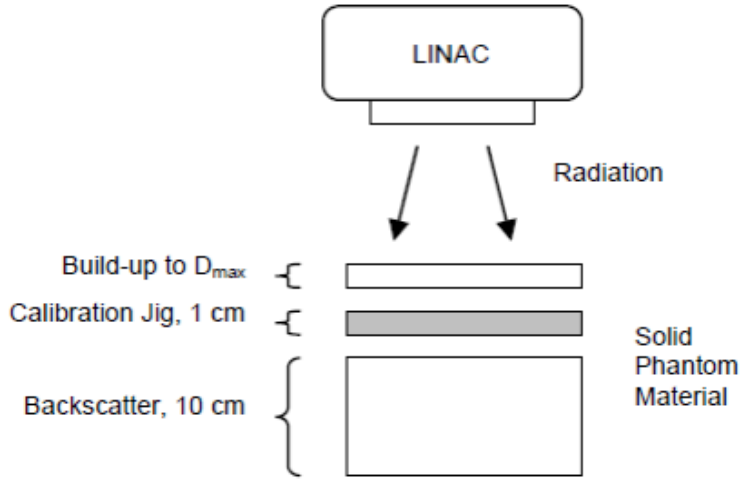
MOSFET Calibration – dosimeter characteristics

- KV Imaging Response

		STD KV CBCT (Pelvis)		High sensitivity Vtg Change (mV)			High sensitivity Dose (cGy)		
MOSFET #	Location	Vtg change (mV)	Dose (cGy)	KV - 270 (15cm dpeth)	KV - 0 (1.5cm dpeth)	KV CBCT (pelvis)	KV - 270 (15cm dpeth)	KV - 0 (1.5cm dpeth)	KV CBCT (pelvis)
1	ISO	17.21	15.94	0	0.48	54.49	0.00	0.14	15.34
2	ISO	20.27	19.12	0	0.29	53.66	0.00	0.08	14.90
3	ISO	17.22	16.40	1.01	0	55.69	0.28	0.00	15.19
4	ISO	18.96	17.89	0	0.71	53.26	0.00	0.20	14.78
5	ISO	16.88	15.92	0	0.71	54.96	0.00	0.20	15.66

Note: Calibration factors of 6MV are used for this calculation

- **MOSFETs exhibit over-response to imaging dose**



Integration with Clinical Workflow

Total Body Irradiation

Planned Dose	Film
151.73 (cGy)	148.7cGy (98%)

MOSFET #	Dose (cGy)	% of Planned Dose
1	151.37	99%
2	154.94	102%
3	145.76	96%
4	148.35	97%
5	149.13	98%
Avg	149.91	99%

TBI Response

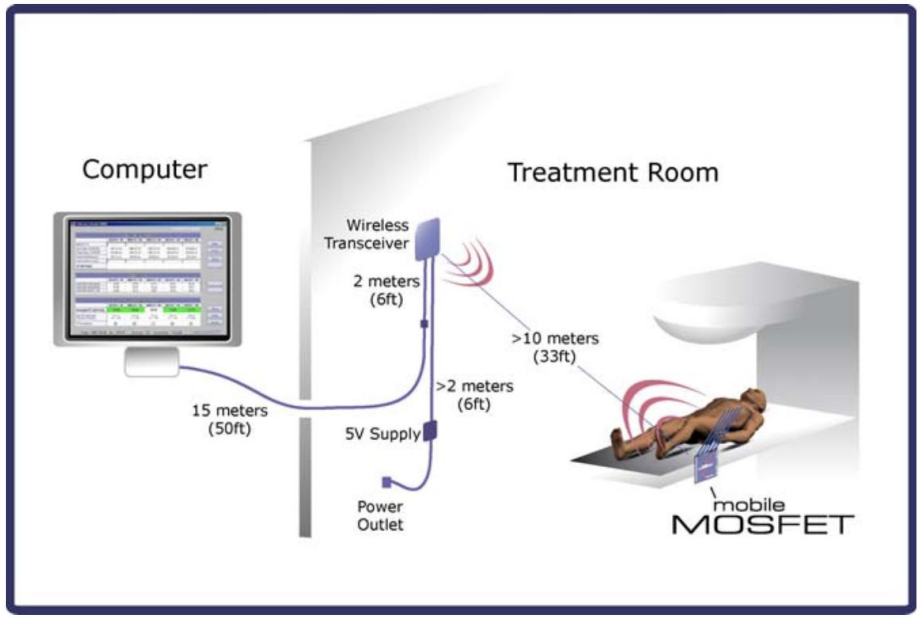
Patient Measurement: MOSFET vs. EBT3 films

	Head Dose (%prescription)			Chest Dose (%prescription)			Umbilicus (%prescription)		
Patient	FILM	MOSFET	Difference	FILM	MOSFET	Difference	FILM	MOSFET	Difference
1	97%	94%	-3%	77%	80%	3%	103%	108%	5%
2	96%	100%	4%	94%	89%	-5%	100%	99%	-1%
3	89%	88%	-1%	87%	84%	-3%	108%	108%	0%
4	86%	88%	2%	84%	93%	9%	95%	103%	8%
5	86%	80%	-6%	97%	96%	-1%	97%	99%	2%
6	88%	86%	-2%	92%	93%	1%	100%	101%	1%
7	97%	94%	-3%	97%	80%	-17%	100%	107%	7%
8	84%	83%	-1%	83%	82%	-1%	93%	101%	8%
9	89%	93%	4%	109%	113%	4%	104%	105%	1%
Avg ± Std			2.89%±1.9%			4.89%±4.5%			3.67%±3.1%

Note: the absolute values of the variations were used to calculate the average and standard deviation

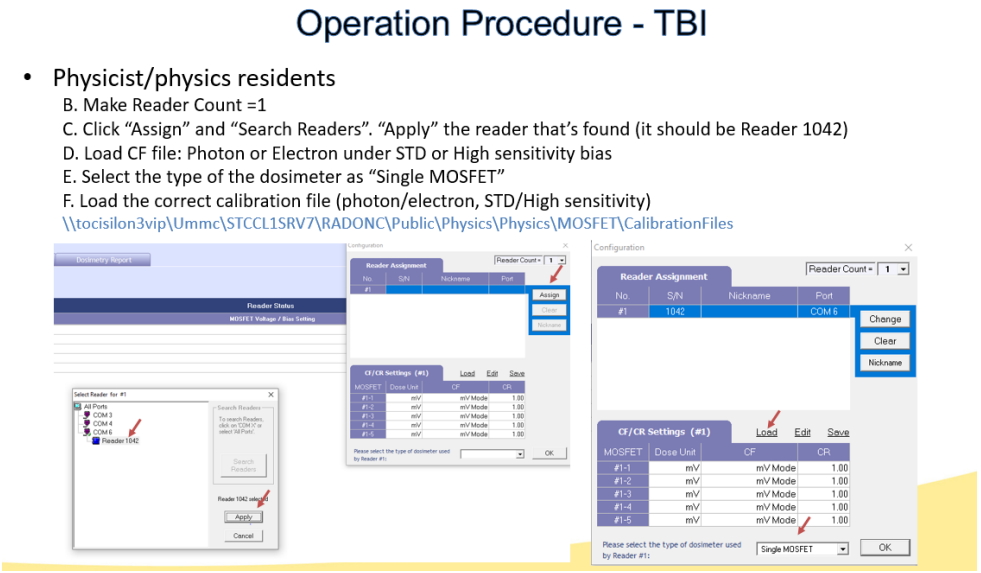
Integration with Clinical Workflow

- Device Setup
  - The portable MOSFET reader communicates with the computer via a wireless Bluetooth receiver, which is connected to the computer through a cable
  - Use the low adhesive surgical tape, e.g. 3M Micropore
  - Make sure the reader is outside the radiation field



Integration with Clinical Workflow

- Standardized procedures should be established for all relevant personnel, including physicists and radiation therapists, and training should be provided
- Exclusion of imaging dose is recommended; this can be achieved by initializing the reader after image acquisition and before treatment delivery



Summary

- ❑ Use STD sensitivity for TBI and central axis dose
- ❑ Use High sensitivity for scattered dose and dose below 20cGy
- ❑ Use individual calibration factor for each dosimeter and for different energies (6X/15X, electrons)
- ❑ High Dose Performance Summary:
  - Combination of reproducibility and energy dependence is ~3.5% for individual dosimeter
  - Linearity <2%
- ❑ Low Dose Performance Summary:
  - Combination of reproducibility and energy dependence is <6.5%
- ❑ Exclude imaging dose for in-vivo measurements, particularly when the expected dose is low

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Thank you!

Questions?