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Modified Electron Beam Calibration : Concept and Implementation

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Outlines

- Concept of Modified Electron Calibration
- Comparison IAEA TRS 398 versus Modified Procedures
- Comparison AAPM TG 51 versus Modified
- Multicenter study of Modified Electron Beam
- Modified Procedure in High Dose Rate Electron Beam

Background

2014 — 2020 — 2022 — 2023 — 2023

Muir et al., 2014
Montecarlo calculation of electron beam quality conversion factor for several ion chamber types

Muir et al., 2020
A modified for electron beam reference dosimetry to improve the accuracy of linac output calibration

Pawiro et al, 2022
Modified electron beam ouput calibration based on IAEA Technical Report Series 398

Yulinar et al., 2023
Modified calibration protocols in electron beam dosimetry : comparison with IAEA TRS-398 and AAPM TG-51

Mahfirotin et al., 2023
A multicenter study of modified electron beam output calibration

IAEA TRS 398 versus AAPM TG 51

IAEA TRS 398,defined:

$$D_{W,Q} = M_Q . N_{D,W,Q0} . k_{Q,Q0}$$

AAPM TG 51 Defined:

$$D_W^Q = M k_Q N_{D,W}^{60Co}$$

$$k_Q = P_{gr}^Q k'_{R50} k_{ecal}$$

$$P_{gr}^Q = \frac{M_{raw}(d_{ref} + 0.5 r_{cav})}{M_{raw}(d_{ref})}$$

$$k'_{R50}(cyl) = 0.9905 + 0.071 e^{R50/3.67}$$

$$k'_{R50}(pp) = 1.2239 - 0.145 (R_{50})^{0.214}$$

Plan parallel Detector→ for low electron energy(6 MeV or less).

Influence quantity	Reference value or reference characteristic
Phantom material	For $R_{50} \geq 4$ g/cm^2, water For $R_{50} < 4$ g/cm^2, water or plastic
Chamber type	For $R_{50} \geq 4$ g/cm^2, plane parallel or cylindrical For $R_{50} < 4$ g/cm^2, plane parallel
Measurement depth z_{ref}	$0.6 R_{50} - 0.1$ g/cm^2
Reference point of the chamber	For plane-parallel chambers, on the inner surface of the window at its centre For cylindrical chambers, on the central axis at the centre of the cavity volume
Position of the reference point of the chamber	For plane-parallel chambers, at z_{ref} For cylindrical chambers, $0.5 r_{cyl}$ deeper than z_{ref}
SSD	100 cm
Field size at phantom surface	10 cm × 10 cm or that used for normalization of output factors, whichever is larger

Modified Protocols

Modified electron beam calibration proposed by Muir:

$$D_W = M k'_Q k_{Q,ecal} N_{D,W}^{60Co}$$

Where k_Q possible to use cross calibration for plan parallel chamber

k'_Q for lan parallel is calculated :

$$k'_Q = a + b \times e^{-R_{50}/c}$$

For cylindrical chamber :

$$k'_Q = a + b \times R_{50}^{-c}$$

$k_{Q,ecal}$ data available in the Muir dan Roger publication (2014)

Methodology

Setting up measurement

Parameter	TRS 398	AAPM TG 51	Modified/ AAPM TG 51	Modified/ TRS 398
Phantom	(30 × 30 × 30) cm^3 water phantom			
Applicator	(10 × 10) cm^2			
Reference depth	$Z_{ref} = 0.6R_{50} - 0.1$ g cm^{-2}			
Chamber Position				
- **Plan Parallel chamber**	- Inner surface of window at center Z_{ref}		- EPOM (effective point of measurement) at Z_{ref}	
- **Cylindrical chamber**	- Central axis $Z_{ref} + 0.5R_{cyl}$	- Central axis at Z_{ref}	- Central axis at Z_{ref}	
MU	100			
SSD	100			

Methodology (2)

Correction Factor

- Corrected Reading :

$$M_Q = M_{raw}.k_{T,P}.k_{pol}.k_s.k_{elec}$$

Correction Factor:

$$k_{T,P} = \frac{(273{,}2 + T).P_0}{(273{,}2 + T_0).P}$$

$$k_{pol} = \frac{|M^+| + |M^-|}{2M}$$

$$k_s = a_0 + a_1\left(\frac{M_1}{}\right) + a_2\left(\frac{M_1}{}\right)^2$$

$$P_{\text{ion}}(V_H) = \frac{1. - V_H/V_L}{M_{\text{raw}}^H/M_{\text{raw}}^L - V_H/V_L}.$$

where,

M_Q = corrected reading (C)

M_{raw} = uncorrected reading (C)

$k_{T,P}$ = Correction factor temperature pressure .

k_{pol} = Correction factor Polarity

k_s = Correction factor recombination

k_{elec} = Calibration factor electrometer

Methodology (3)

Absorbed dose :

1. AAPM TG 51

$$D_W^Q = MP_{gr}^Q k'_{R50} k_{ecal} N_{D,W}^{60Co}$$

2. TRS 398

$$D_{W,Q} = M_Q . N_{D,W,Q0} . k_{Q,Q0}$$

3. Modified (Muir, 2020):

$$D_W = Mk'_Q k_{Q,ecal} N_{D,W}^{60Co}$$

Depth dose maximum :

$$D_{W,Q}(zmax) = \frac{100xD_{W,Q}(zref)}{(PDD_{(zref)})}$$

Reference depth dose maximum is 1 cGy/MU

Dose discrepancy :

$$Deviation = (D_{w,q}(zmax) - 1)x100\%$$

We analysed the depth dose maximum based on TRS 398 and TG 51 compared to modified procedure

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Result : Quality Factor (1)

Beam Quality Factor $k_{Q,Q0}$ - IAEA TRS-398

Linear Accelerator	**Energy (MeV)**	$\mathbf{R_{50}}$ **(cm)**	$\mathbf{k_{Q,Q0}}$		
			PTW 30013	**IBA CC13**	**Exradin A11**
Synergy Platform	6	2,47	-	-	0,930
	8	3,23	-	-	0,921
	10	3,95	0,911	0,920	0,914
	12	4,74	0,908	0,918	0,906
	15	5,77	0,905	0,914	0,899
Versa HD	6	2,43	-	-	0,931
	8	3,22	-	-	0,921
	10	3,94	0,911	0,920	0,914
	12	4,65	0,908	0,918	0,907
	15	5,83	0,905	0,914	0,898

- Value $k_{Q,Q0}$ mentioned at Table 7.III (or 18) IAEA TRS-398 which is calculated according to ***stopping-power ratios***
- $k_{Q,Q0}$ only for 10, 12, dan 15 MeV and for PTW 30013 dan IBA CC13.

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Result : Beam Quality Factor (2)

Beam Quality Factor $k_{Q,Q0}$ according to AAPM TG-51

Linear Accelerator	Energy (MeV)	R_{50} (cm)	k'_{R50}		
			PTW 30013	IBA CC13	Exradin A11
Synergy Platform	6	2,47	1,027	1,027	1,045
	8	3,23	1,020	1,020	1,033
	10	3,95	1,015	1,015	1,024
	12	4,74	1,010	1,010	1,015
	15	5,77	1,005	1,005	1,005
	Q_{ecal}	7,5	k_{ecal}		
			0,897	0,904	0,888
Versa HD	6	2,43	1,027	1,027	1,045
	8	3,22	1,020	1,020	1,033
	10	3,94	1,015	1,015	1,024
	12	4,65	1,011	1,011	1,016
	15	5,83	1,005	1,005	1,005
	Q_{ecal}	7,5	k_{ecal}		
			0,897	0,904	0,888

- TG-51reccommed only cylindrical chamber for high energy electron (6 MeV or higher)
- Beam Quality Factor for TG-51 consist of gradient correction factor, conversion quality factor, and conversion photon – electron

Result : Beam Quality Factor

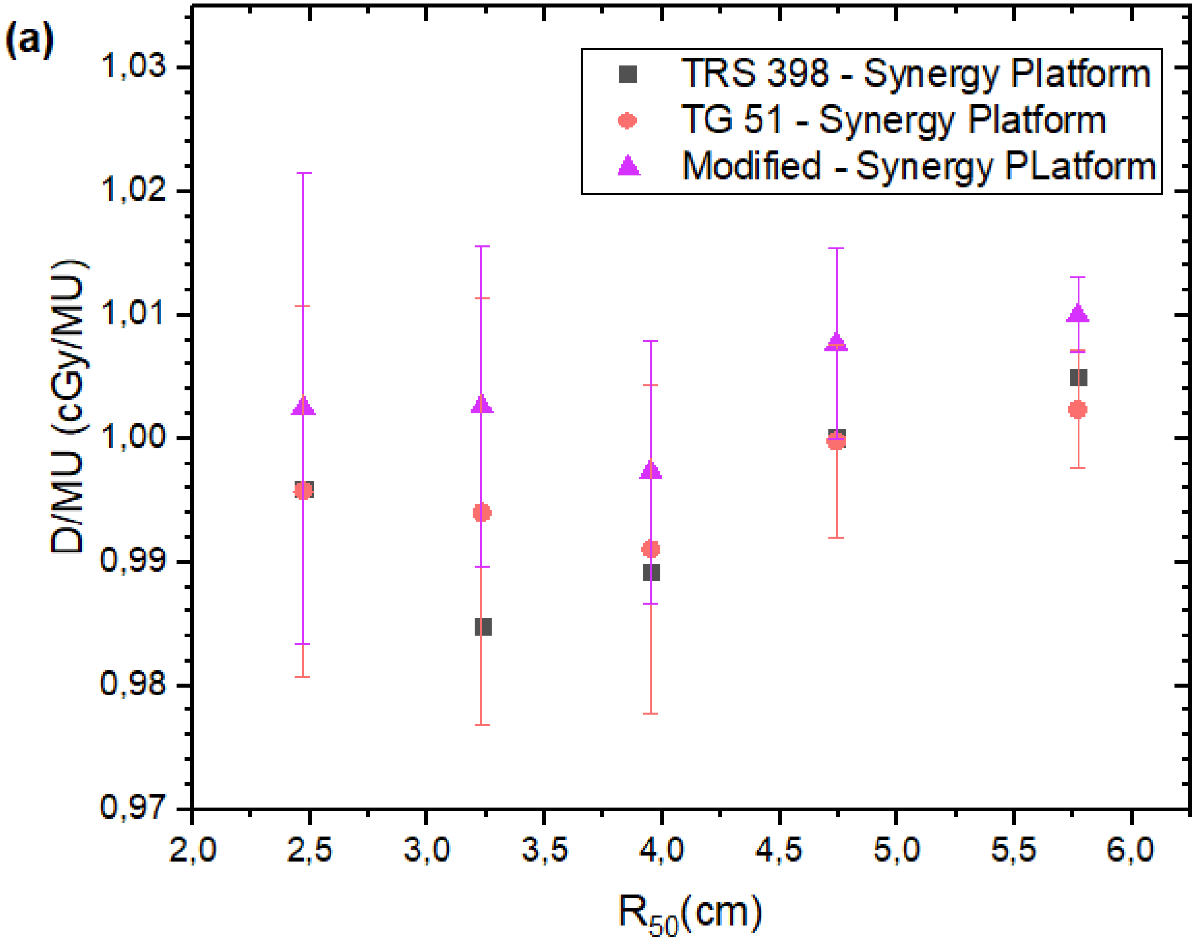
Beam Quality Factor $k_{Q,Q0}$ based on Modified procedure

Linear Accelerator	Energy (MeV)	R_{50} (cm)	k'_Q		
			PTW 30013	IBA CC13	Exradin A11
Synergy Platform	6	2,47	1,032	1,026	1,040
	8	3,23	1,021	1,019	1,029
	10	3,95	1,015	1,014	1,021
	12	4,74	1,010	1,010	1,014
	15	5,77	1,005	1,005	1,007
	Q_{ecal}	7,5	$k_{Q,ecal}$		
			0,901	0,904	0,906
Versa HD	6	2,43	1,045	1,032	1,032
	8	3,22	1,033	1,024	1,021
	10	3,94	1,024	1,018	1,015
	12	4,65	1,016	1,013	1,010
	15	5,83	1,005	1,007	1,005
	Q_{ecal}	7,5	$k_{Q,ecal}$		
			0,901	0,904	0,906

- Beam quality conversion factor is generated by Monte Carlo proposed by Muir
- k'_Q factor varied depend on detectors and R_{50}, because the simulation were performed based on geometry and detector materials

Result : Absorbed Dose – Synergy Platform

- Depth dose maximum (dose rate, D/MU) was presented in the Figure
- Modified Protocols gave the average deviation 1,06%. is more higher from TRS-398 (0,48% for Synergy Platform) dan TG-51 (1,03% for Synergy Platform)



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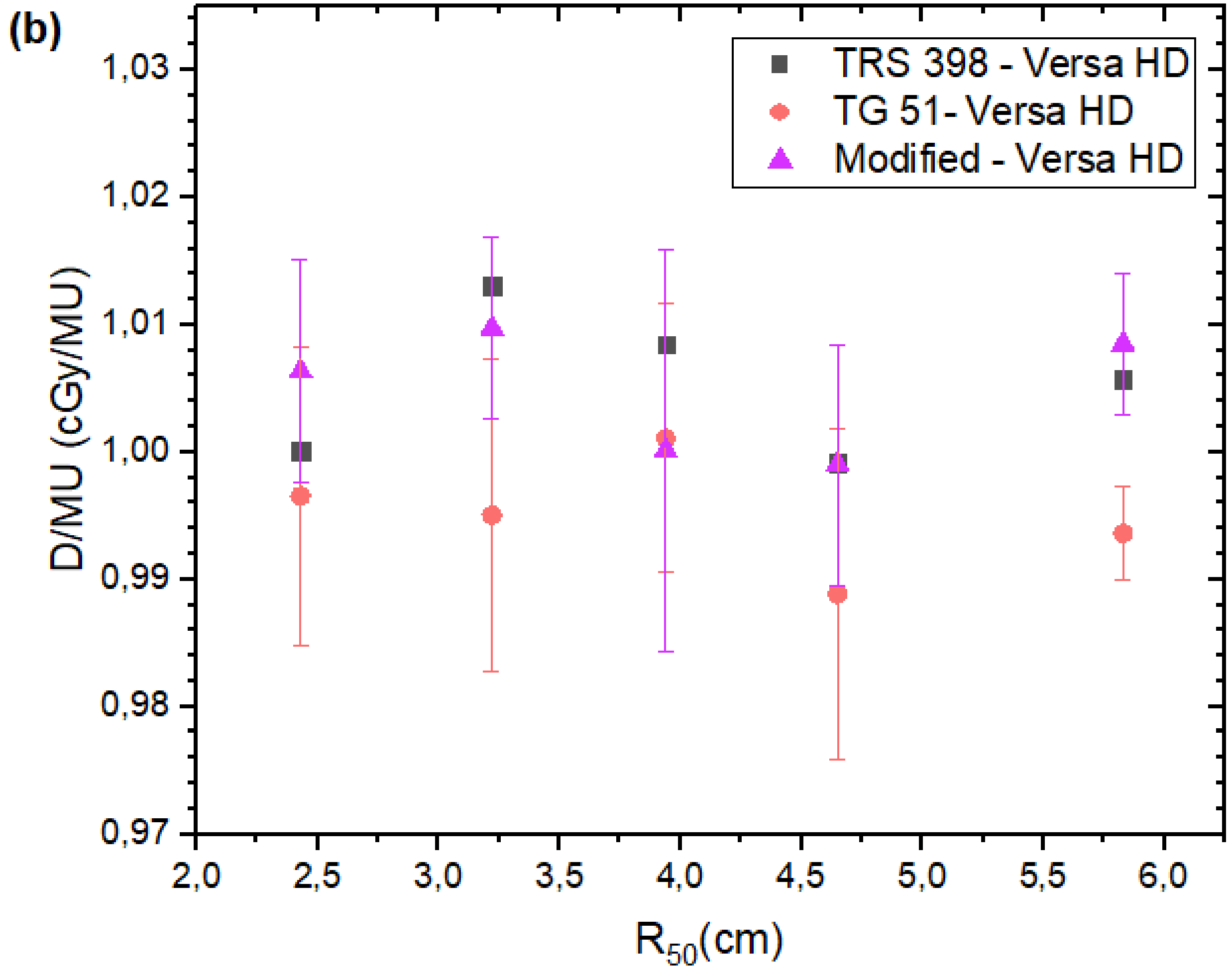
Result : Absorbed Dose – Versa HD

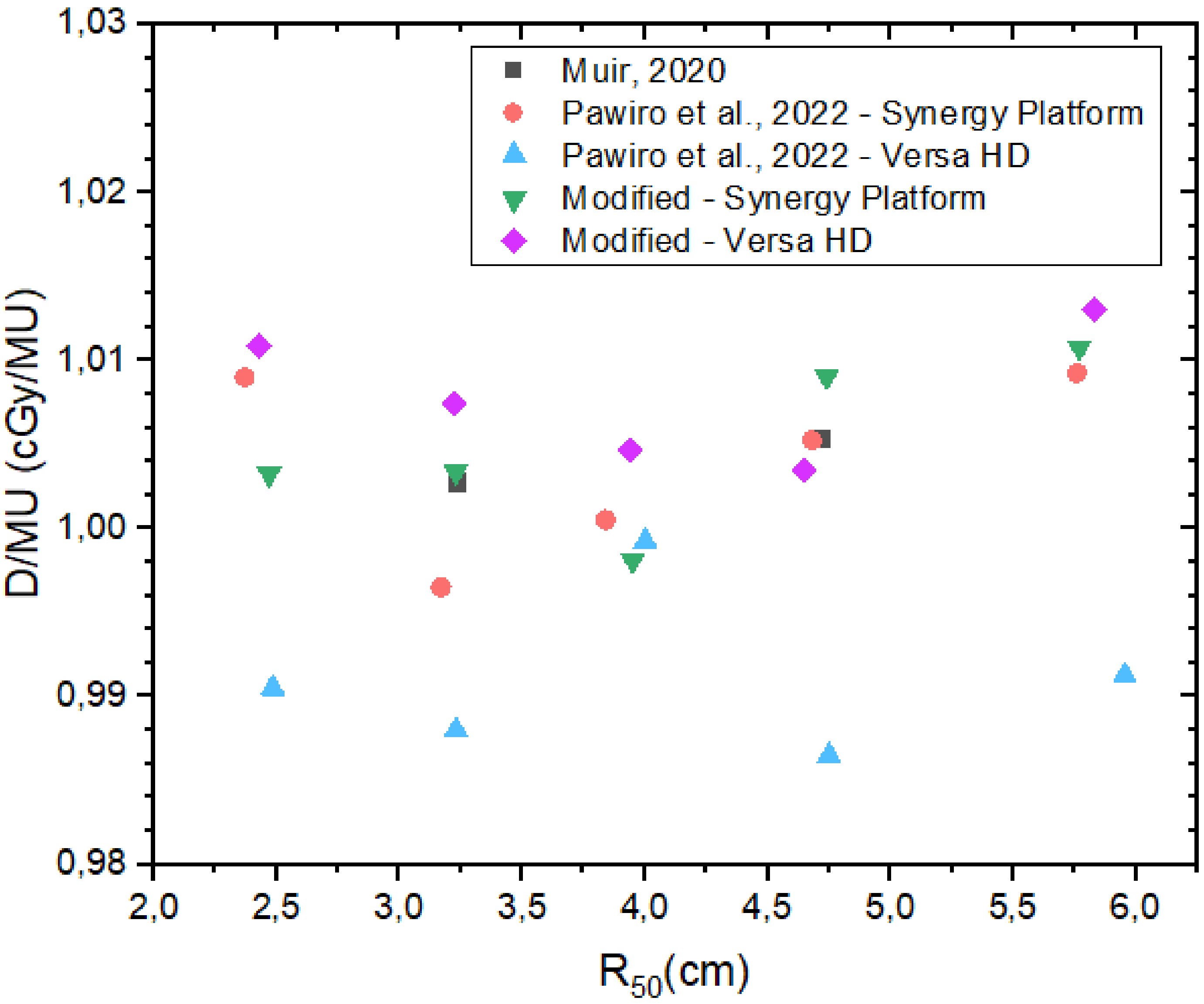


For Versa HD, Modified Protocols gave the average deviation around 0,9%, smaller than TRS-398 (1,03%%) and TG-51 (1,17%)

Result : Ratio Absorbed dose Modified Protocols (1)

Modified Protocols implementation :

- 0,4% (Muir, 2020)
- 0,4–0,5% (Pawiro et al., 2022),
- 0,9–1,06 % Yulinar et al (2023)



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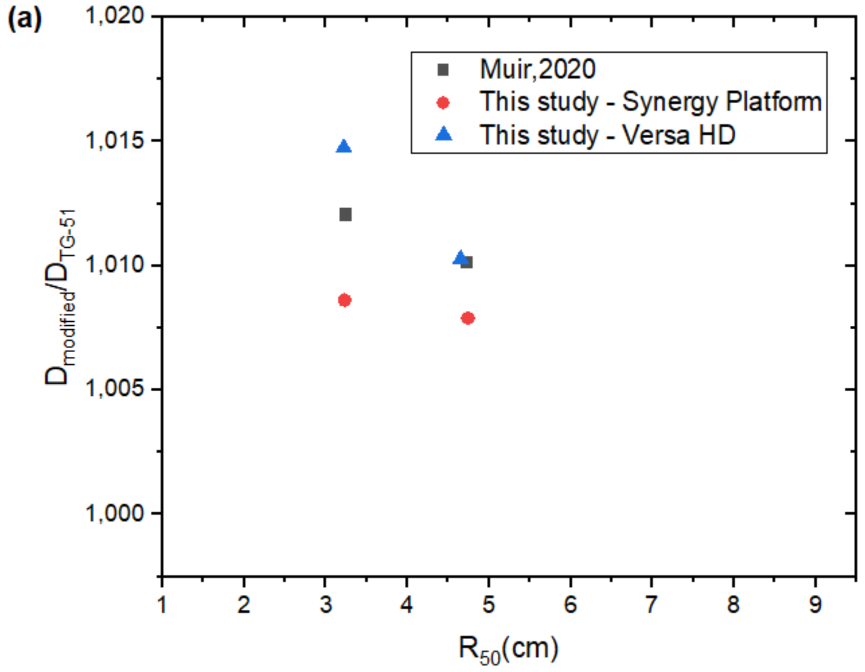
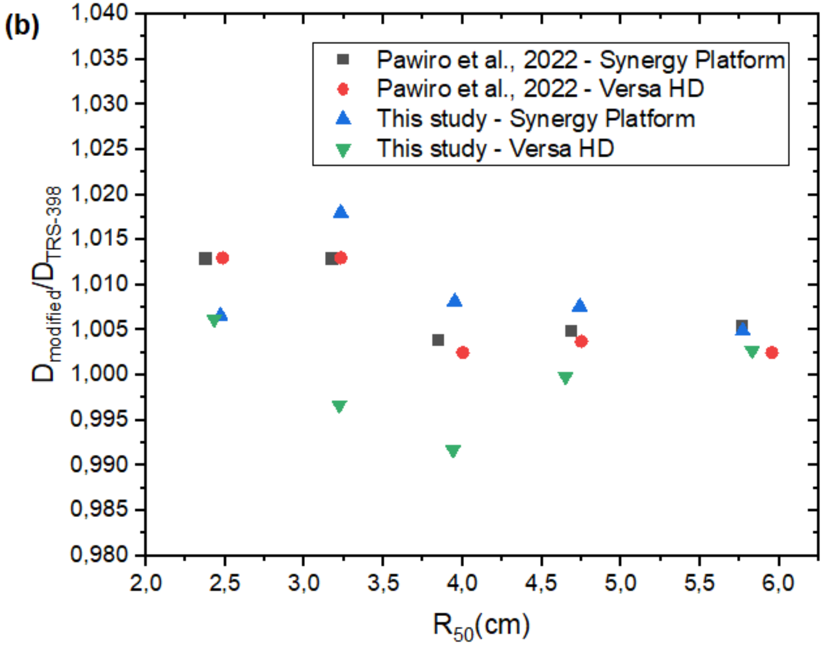
Result : Ratio Absorbed dose Modified Protocols (2)

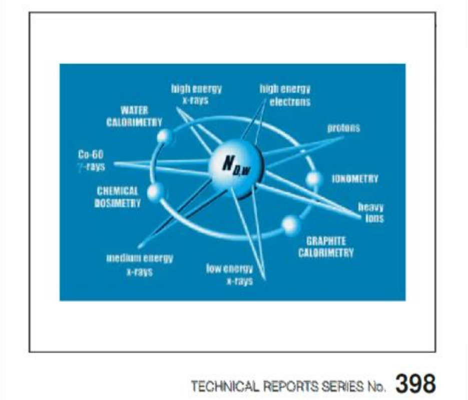
- The average discrepancy ratio dose rate modified protocol / TG 51 is **0,27%** (Figure [a]).
- The average discrepancy ratio dose rate modified protocol /TRS-398 from Pawiro et al. is **0,56%** (Figure [b]).

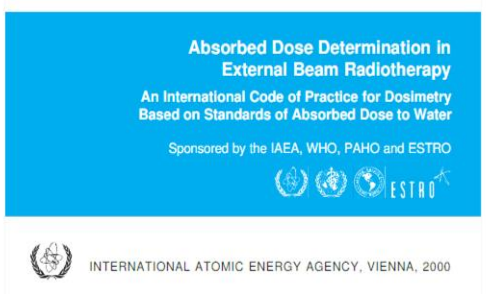




Multicenter Study of Modified Electron Beam Calibration

Introduction

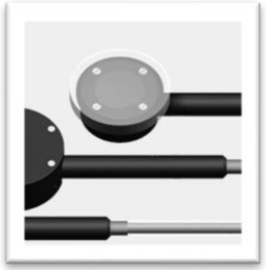




International Atomic Energy Agency (IAEA) TRS-398 is a protocol of clinical reference dosimetry for high-energy photon and electron beams.

Factor of kQ based on the protocol has been shown to have a 1.7% difference compared to the more accurate Monte Carlo calculations *(Buckley, 2006).*

The overall uncertainty of calculated beam quality correction factors using Monte Carlo calculations was estimated to be <0.7% *(Muir and Rogers, 2013)*



TRS-398 recommends using parallel-plate chambers for electron beam dosimetry ➔ minimize fluence perturbation (Burns DT et al, 1998).

The results of variability of perturbation corrections for cylindrical chambers is 0.4%, which is not significantly different from parallel-plate chambers with the same specifications *(Muir and Ewen, 2017).*

Modified Calibration

Suggested that the cylindrical chamber could be used as reference dosimetry for all electron beam energies. **This is to make electron beam dosimetry measurements simpler and easier because it has a procedure similar to photon beam dosimetry measurements.** *(Muir, 2020)*

Compared the absolute dose ratio using modified calibration procedure and TRS-398 protocols. The results showed that the absolute dose ratios obtained with the cylindrical chamber were 1.002 and 1.004 *(Pawiro et al, 2022)*

Materials

Cylindrical Ionization Chambers :

- 2 Farmer (30013)
- 4 Scanditronix / Wellhofer Farmer (FC65-G)
- 1 Scanditronix / Wellhofer Farmer (FC65-P)

Linear Accelerator types:

- 1 Synergy Platform
- 1 Precise
- 2 Versa HD
- 1 Clinac iX
- 2 Trilogy

Parallel-Plate Chambers :

- 1 Advanced Markus (34045)
- 1 Ross (34001)
- 5 Scanditronix / Wellhofer (PPC-40)

UNIDOS, Tandem (PTW, Germany) and Dose-1 (IBA, GmBH, Scanditronix Wellhofer, Germany) electrometer models

PTW Beam Scan Lift, Sun Nuclear 3D Scanner, IBA Water Phantom 1D, Sun Nuclear 1D Scanner,

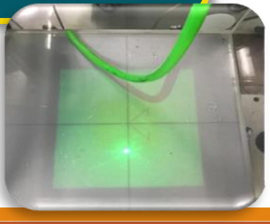
A $10 \times 10cm^2$ applicator

Termometer, Barometer

Methods

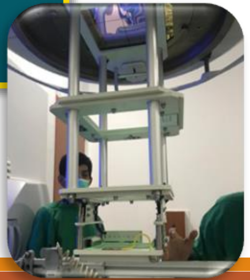
A Preparation and Setting of Experimental Equipment

1. Positioning the water phantom right on the cross-wire



2. Filling water into the water phantom

3. Install the 10 x 10 cm applicator



4. Place the ionization chamber according to the reference point

TRS-398

Parallel-plate chamber → Zref
Cylindrical chamber → Effective Point of Measurement

Modified

Cylindrical chamber → Zref

5. Positioning the isocentre or cross-wire of the chamber

6. Determine SSD of 100 cm

7. Place the thermometer and barometer in measurement area

Methods

B Experimental Measurement and Calculation

8

Unidos & Tandem Electrometer → Farmer Chamber (30013)

Dose-1 Electrometer → Scanditronix / Wellhofer Farmer Chambers (FC65-G, FC65-P & PPC-40), Advanced Markus Chamber (34045) and Ross Chamber (34001)

9

The operating voltages for the chambers were ±400 V, ±300 V , ± 150 V and 100 V,

10

The linear accelerators were operated at a dose rate of 200 MU/min.

11

Record the raw charge reading measurement (nC)

12

Calculate the correction factor

Ktp, Kpol, Ks, Kelec

Methods

- Determination of the beam quality correction factor and absorbed dose to water

TRS-398 Protocol

Modified Calibration

$k_{Q,Qo}$ = from the table of 7.III IAEA TRS-398

$$D_{w,Qo}(z_{ref}) = M_{Qo}\, N_{D,w,Qo}\, k_{Q,Qo}$$

TABLE VII. Power fitting parameters for cylindrical chambers [k'_Q vs R_{50} of the form in Eq. (11)] when results are obtained using only clinical accelerator models

Manufacturer	Chamber	Power fitting parameters *a*	*b*	*c*	RMSD (%)
NE	2571	0.977	0.117	0.817	0.15
	2611	0.979	0.120	0.875	0.09
Exradin	A12	0.965	0.119	0.607	0.11
	A19	0.957	0.119	0.505	0.14
	A12S	0.937	0.136	0.378	0.13
	A18	0.352	0.711	0.046	0.11
	A1SL	0.205	0.854	0.036	0.13
PTW	30010	0.980	0.119	0.891	0.14
	30011	0.976	0.120	0.793	0.13
	30012	0.972	0.121	0.728	0.11
	30013	0.978	0.112	0.816	0.15
	31013	0.945	0.133	0.441	0.15
IBA	FC65G	0.971	0.113	0.680	0.13
	FC65P	0.973	0.110	0.692	0.14
	FC23C	0.971	0.097	0.591	0.16
	CC25	0.964	0.105	0.539	0.16
	CC13	0.926	0.129	0.279	0.10
Capintec	PR06C/G	0.972	0.122	0.729	0.14

Manufacturer	Chamber	$k_{Q,ecal}$ No P_{gr}^{Q} Clinical beams
NE	2571	0.903
	2611	0.896
Exradin	A12	0.907
	A19	0.904
	A12S	0.907
	A18	0.914
	A1SL	0.914
PTW	30010	0.904
	30011	0.901
	30012	0.908
	30013	0.901
	31013	0.902
IBA	FC65G	0.904
	FC65P	0.902
	FC23C	0.904
	CC25	0.904
	CC13	0.904
Capintec	PR06C/G	0.906

Muir and Rogers (2014)

$$k'_Q = a + b \times R_{50}{}^{-c}$$

$$D_{w,Q(Zref)} = M\, k'_Q\, k_{Q,ecal}\, N_{D,w}^{Co}$$

$$D_{w,Q}\,(z_{max}) = \frac{100 \times D_{w,Q}(z_{ref})}{(PDD_{(Zref)})}$$

Results

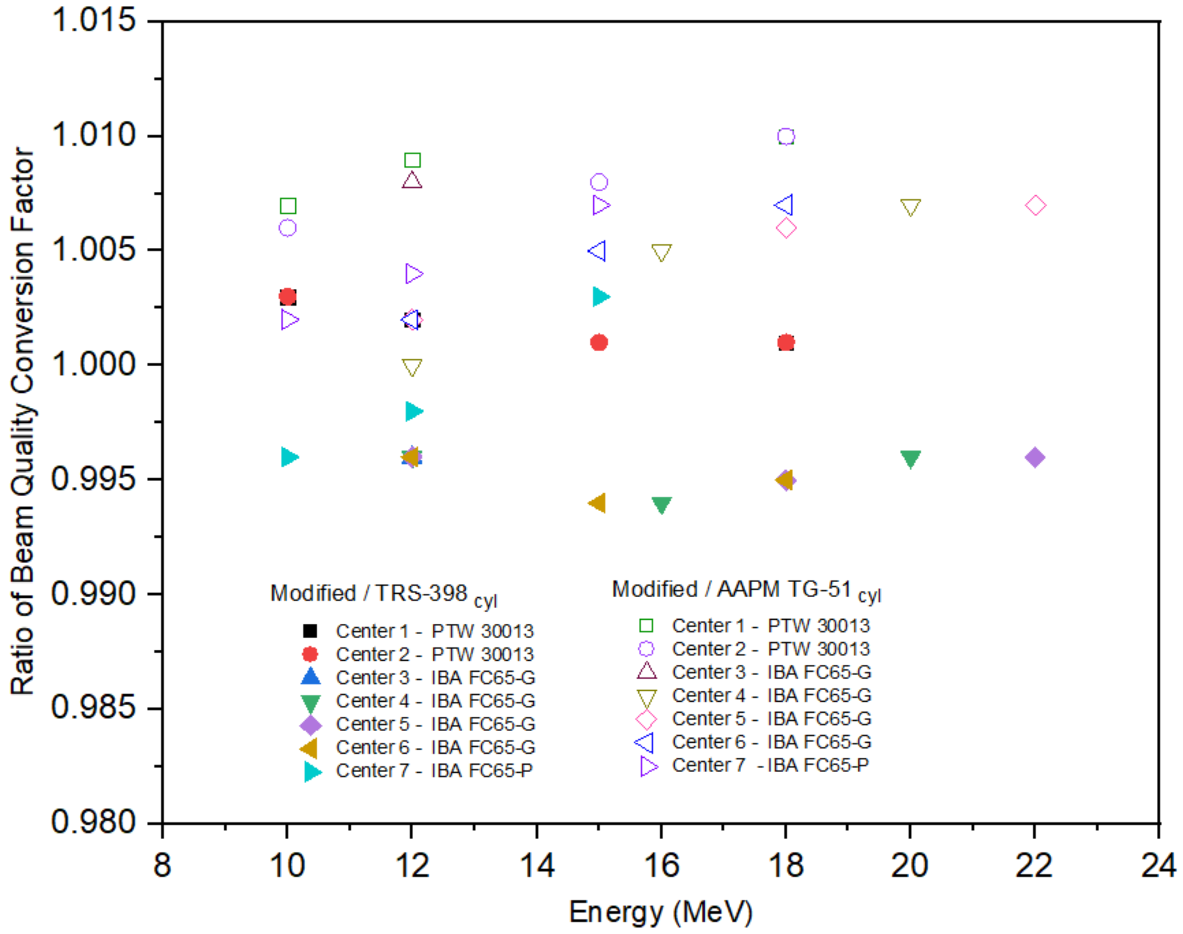


Figure 1. The ratio of beam quality correction factors of cylindrical chamber using modified calibration to TRS-398 and TG-51

- The ratio of beam quality correction factor of modified to TRS-398$_{cyl}$ in the range of 0.994 to 1.003
- The ratio of beam quality correction factor of modified to TG-51cyl in the range of 1.000 to 1.010

Monte Carlo calculated k'_Q factors should be more accurate because ionization chambers can be reliably modelled.

The factor k'_Q in the modified calibration using Monte Carlo calculation incorporated detailed information about the ionization chamber to better reflect the actual geometry.

Muir & Rogers, 2010

Results

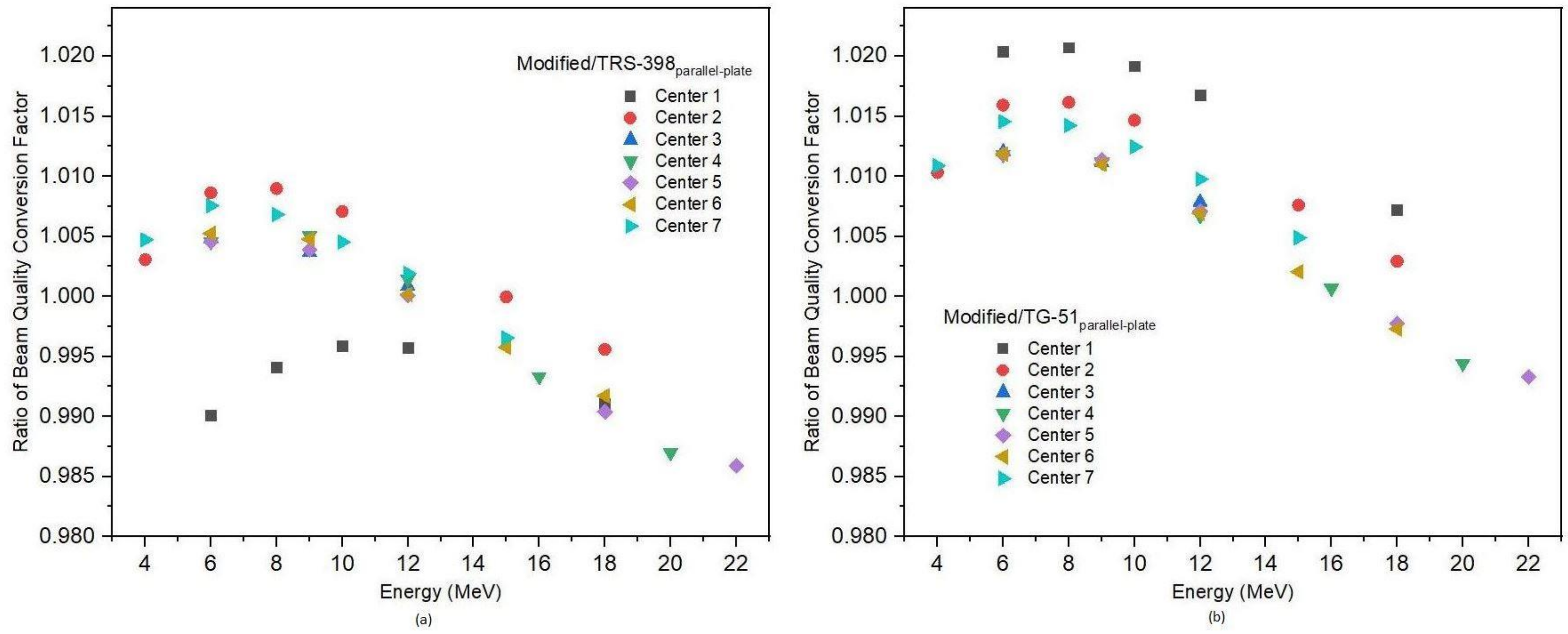


Figure 2. The ratio of beam quality conversion factors of parallel-plate chambers using (a) modified calibration to TRS-398 and (b) modified calibration to TG-51

- The ratio of beam quality correction factor of modified to TRS-$398_{\text{parallel-plate}}$ in the range of 0.986 to 1.009
- The ratio of beam quality correction factor of modified to TG-51parallel-plate in the range of 0.993 to 1.021

- Figure 3 (a) shows a results of dose per monitor unit are varying from 0.980 – 1.022 cGy/MU.

- Figure 3 (b) show results of dose per monitor unit obtained by TRS-398 using cylindrical chamber and parallel-plate chamber. The dose per monitor unit in low energy beams (E ≤ 10 MeV) is only the contribution from the data for parallel-plate chamber. The results of dose/MU are varying from 0.982 – 1.020 cGy/MU and 0.989 – 1.012 cGy/MU for cylindrical chamber and parallel-plate chambers, respectively.

- Figure 3 (c) show a results of dose per monitor unit obtained by TG-51 using cylindrical and parallel-plate chamber.

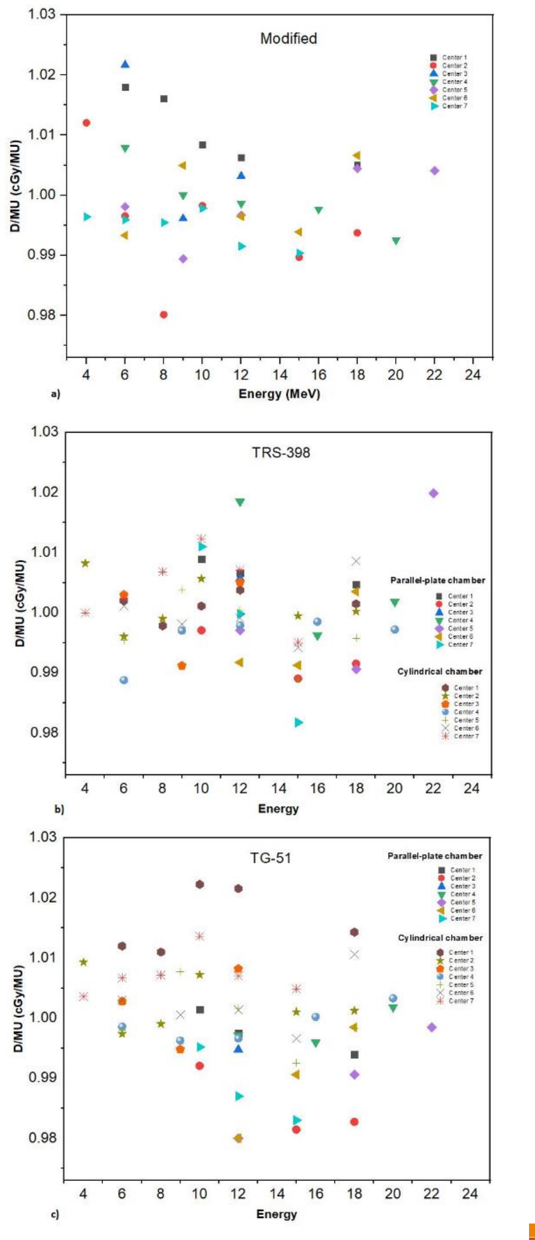


Figure 3. The dose per monitor unit obtained by three methods (a) modified calibration, (b) TRS-398 and (c) TG-51

Center	Energy (MeV)	Modified/TRS-398cyl	Modified/TRS-398parallel-plate	Modified/TG-51cyl	Modified/TG-51parallel-plate
1	6	-	1.016	-	1.006
	8	-	1.018	-	1.005
	10	0.999	1.007	1.007	0.986
	12	1.000	1.002	1.009	0.985
	18	1.000	1.004	1.011	0.991
2	4	-	1.004	-	1.003
	6	-	1.000	-	0.999
	8	-	0.981	-	0.981
	10	1.001	0.993	1.006	0.991
	15	1.001	0.990	1.008	0.989
	18	1.002	0.994	1.011	0.993
3	6	-	1.019	-	1.019
	9	-	1.005	-	1.001
	12	0.998	0.998	1.008	0.995
4	6	-	1.019	-	1.009
	9	-	1.003	-	1.004
	12	0.980	1.001	1.001	1.002
	16	1.001	0.999	1.001	0.997
	20	0.991	0.995	0.991	0.989
5	6	-	1.003	-	1.000
	9	-	0.986	-	0.982
	12	1.000	0.996	1.017	0.995
	18	1.014	1.016	1.014	1.012
	22	0.984	1.008	1.006	1.006
6	6	-	0.992	-	0.990
	9	-	1.007	-	1.004
	12	1.005	0.997	1.017	0.995
	15	1.003	1.000	1.003	0.997
	18	1.003	0.99	1.008	0.996
7	4	-	0.996	-	1.000
	6	-	0.994	-	1.002
	8	-	0.989	-	1.007
	10	0.987	0.986	1.003	1.012
	12	0.992	0.985	1.005	1.007
	15	1.009	0.995	1.007	0.995

- Table 6 shows the dose ratio of modified calibration to TRS-398 and TG-51 protocols.
- The dose ratio of modified/TRS-398_{cyl} at Centers 1, 2, 3, 4, 5, 6, and 7 resulted in minimum and maximum value of 0.980 – 1.014, while the dose ratio of modified/TG-51_{cyl} resulted in 0.991 – 1.017.
- The dose ratio of modified/TRS-$398_{parallel\text{-}plate}$ has resulted in the range of 0.981 – 1.019, while the dose ratio of modified/TG-$51_{parallel\text{-}plate}$ has resulted in the range of 0.981 – 1.019.

Conclusion

- The study found that all cylindrical chambers' beam quality conversion factor determined with the modified calibration (k'_Q) when compared to the TRS-398 and TG-51 vary from 0.994 – 1.003 and 1.000 – 1.010, respectively.
- The dose ratio of modified/TRS-398$_{cyl}$ and modified/TRS-398$_{parallel\text{-}plate,}$ are in 0.980 - 1.014 and 0.981 – 1.019 range, while for the counterpart modified/TG-51$_{cyl}$ was found vary between 0.991 and 1.017 and the ratio of modified/TG-51$_{parallel\text{-}plate}$ was vary in the range of 0.981 – 1.019.
- Overall, the modified electron beam calibration that applied in multicenter radiotherapy give a consistent and good result (below the tolerance that mentioned by TRS-398 >2%).

Modified Electron Beam Calibration in High Dose Rate Electron Beam

Motivation

A

Bruggomosser et al., 2007

There is linear relation between dose per pulse and ion recombination correction factor (P_{ion}) in electron beam

B

Firmansyah et al., 2017

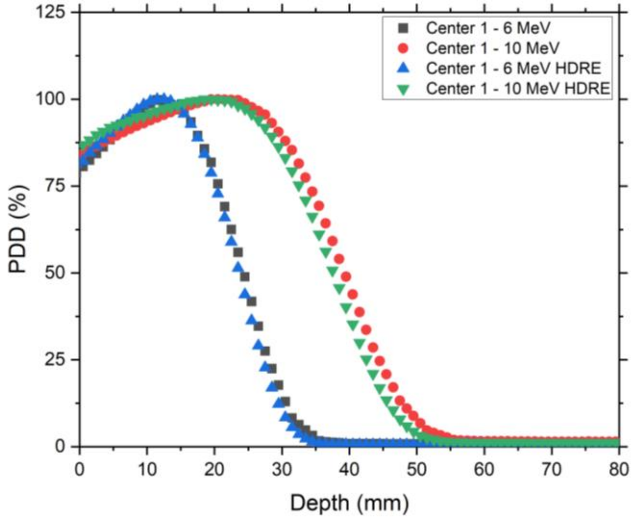
Linac Elekta Versa HD with energy 6 dan 10 MeV produce electron beam with dose rate 10 times compared to conventional electron beam

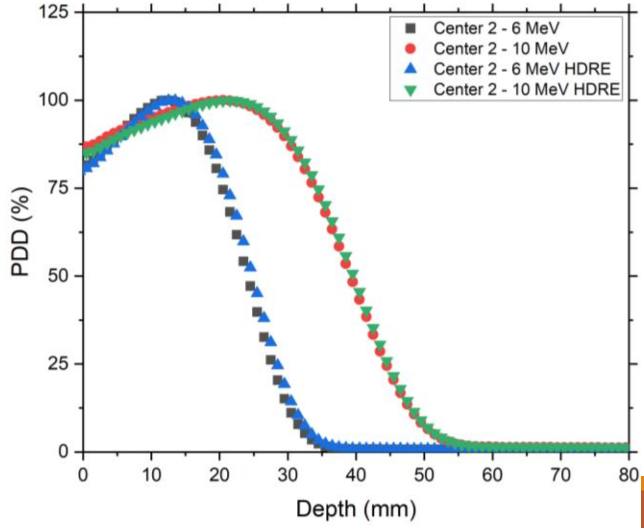
C

Gibbons et al., 2020

High dose rate electron beam induced the recombination ion correction factor (P_{ion}) higher compared to conventional electron beam

High Dose Rate Electron Beam Characteristics





Institution 1

Mode	Energi (MeV)	R_{100} (cm)	R_{50} (cm)	R_{85} (cm)	R_p (cm)
Standar	6	1,17	2,45	1,88	3,17
	10	1,98	3,95	3,18	4,90
HDRE	6	1,17	2,35	1,84	2,94
	10	1,97	3,77	3,07	4,52

Institution 2

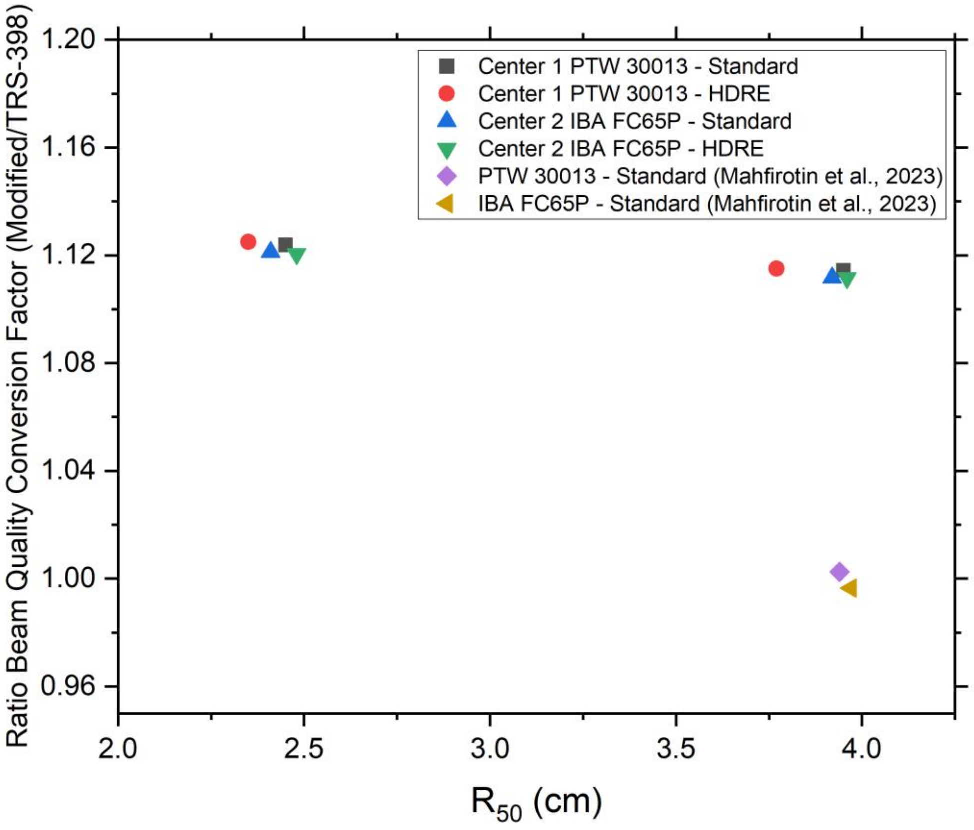
Mode	Energi (MeV)	R_{100} (cm)	R_{50} (cm)	R_{85} (cm)	R_p (cm)
Standar	6	1,27	2,41	1,87	3,08
	10	2,08	3,92	3,11	4,90
HDRE	6	1,28	2,48	1,94	3,17
	10	2,20	3,96	3,17	4,91

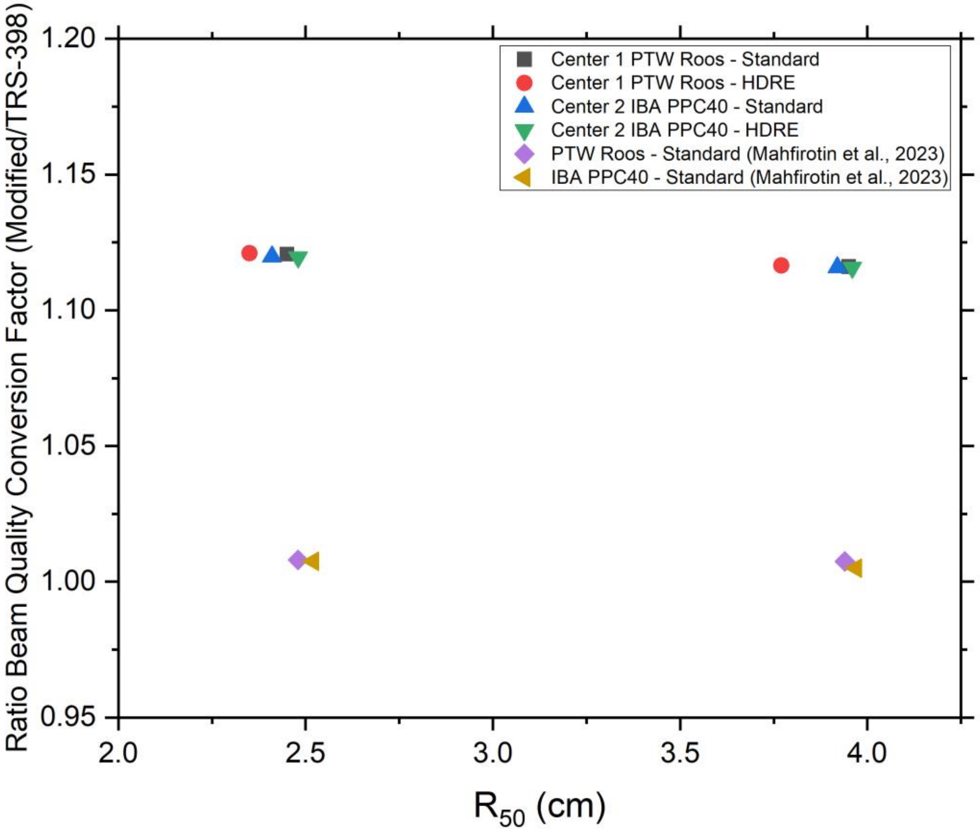
Recombination Ion Correction Factor

Institusi	Detector	Energy (MeV)	Descrepancy (%)		
			TRS 398	TG-51	Modifikasi
Institution 1	PTW 30013	6	5,31	5,00	5,00
		10	5,33	5,06	5,06
	PTW Roos	6	4,69	4,68	4,52
		10	5,06	4,97	4,61
Institution2	IBA FC65P	6	3,51	3,37	3,37
		10	3,36	3,22	3,22
	IBA CC13	6	3,04	2,95	2,95
		10	2,88	2,91	2,91
	IPA PPC40	6	0,85	0,87	0,77
		10	0,77	0,78	0,87

Discrepancy (%) = $((P_{ion-HDRE} - P_{ion-standar})/ P_{ion-standar}))$ * 100%

Quality Beam Factor



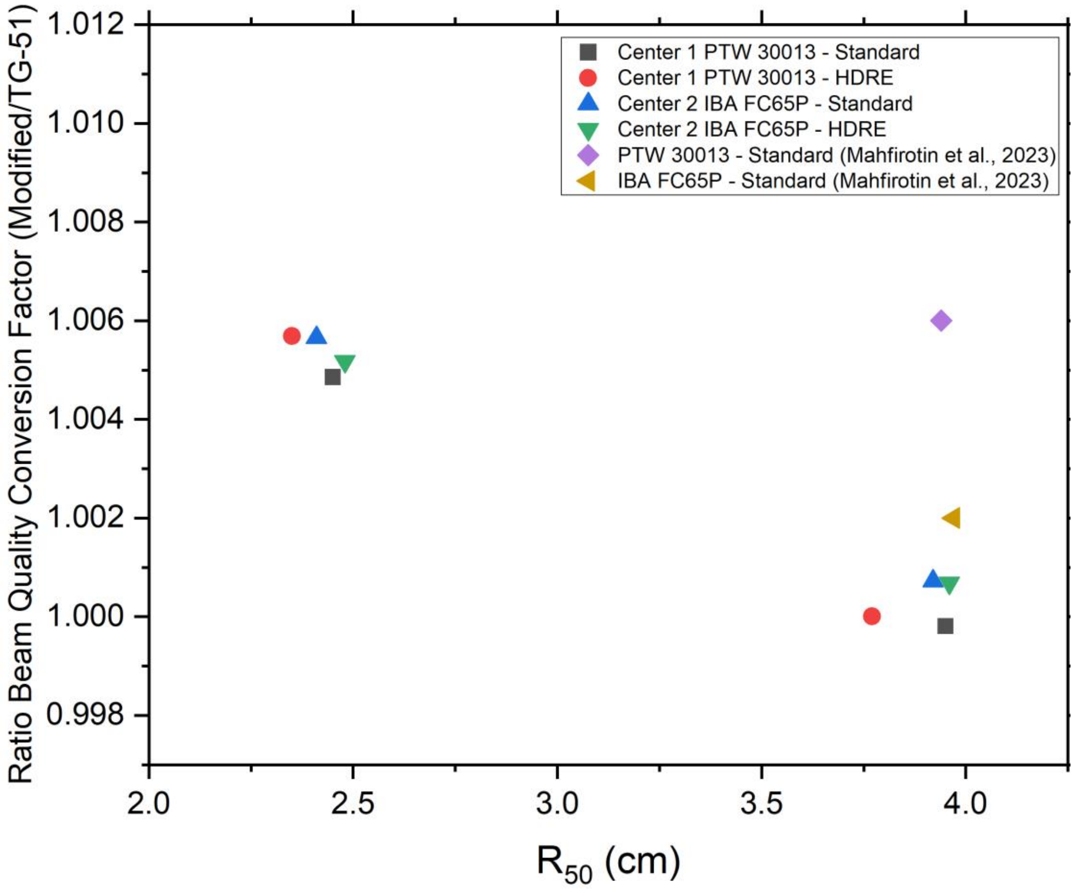


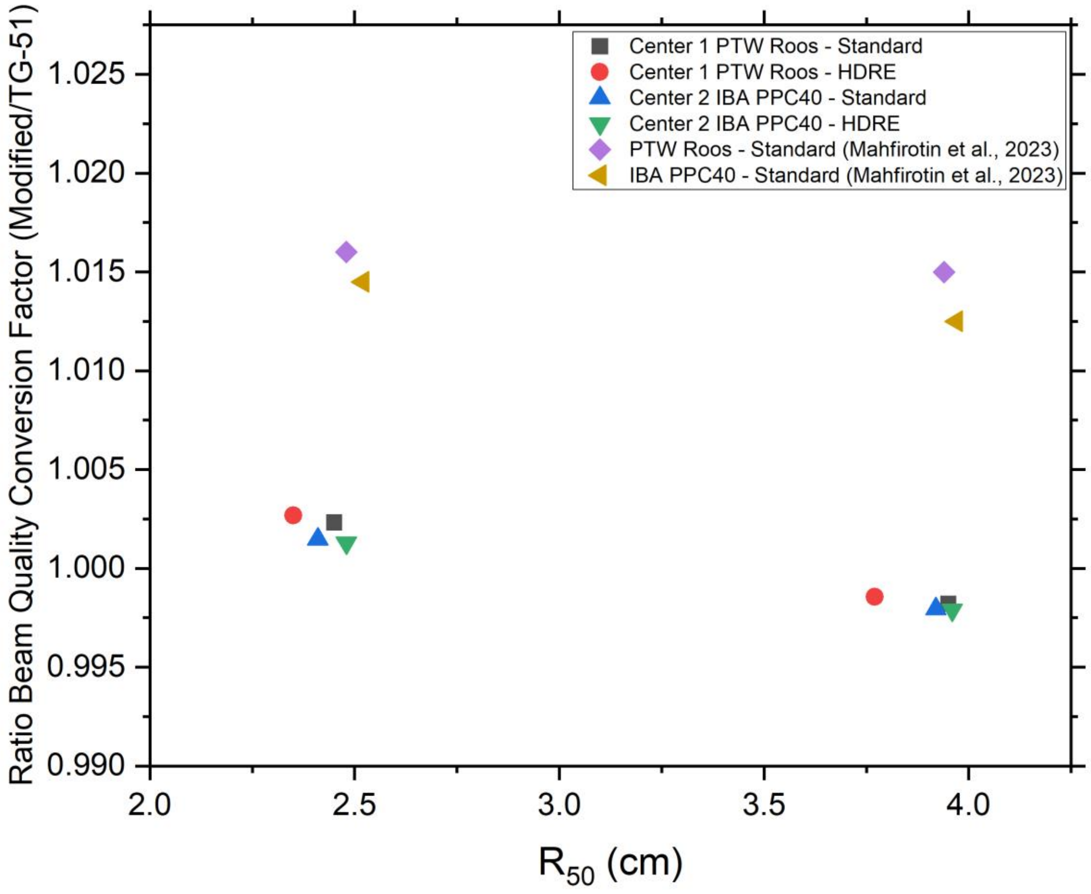
❖ TRS-398 versus Modified :

Cylindrical Detector: 1.10-1.125

Plan Parallel Detector: 1.116 – 1.121

Quality Beam Factor



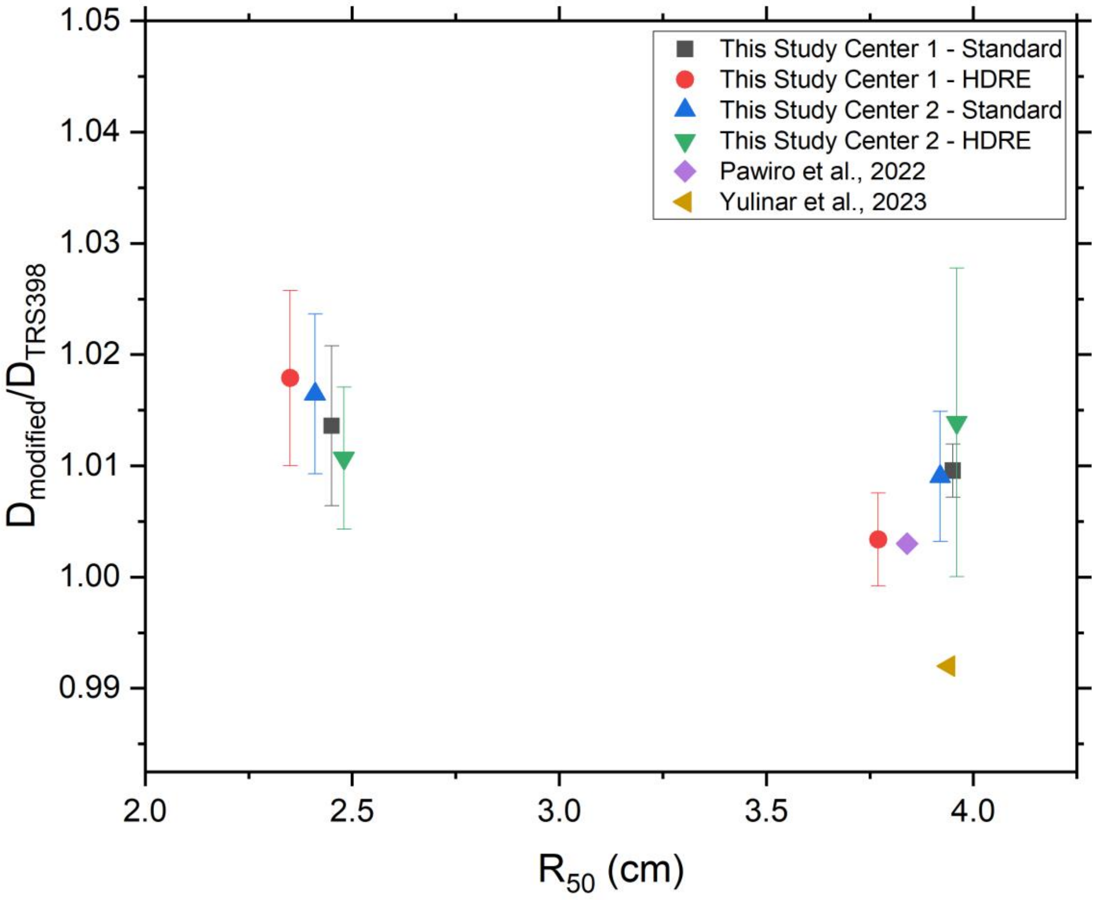


❖ TG-51 versus modified :

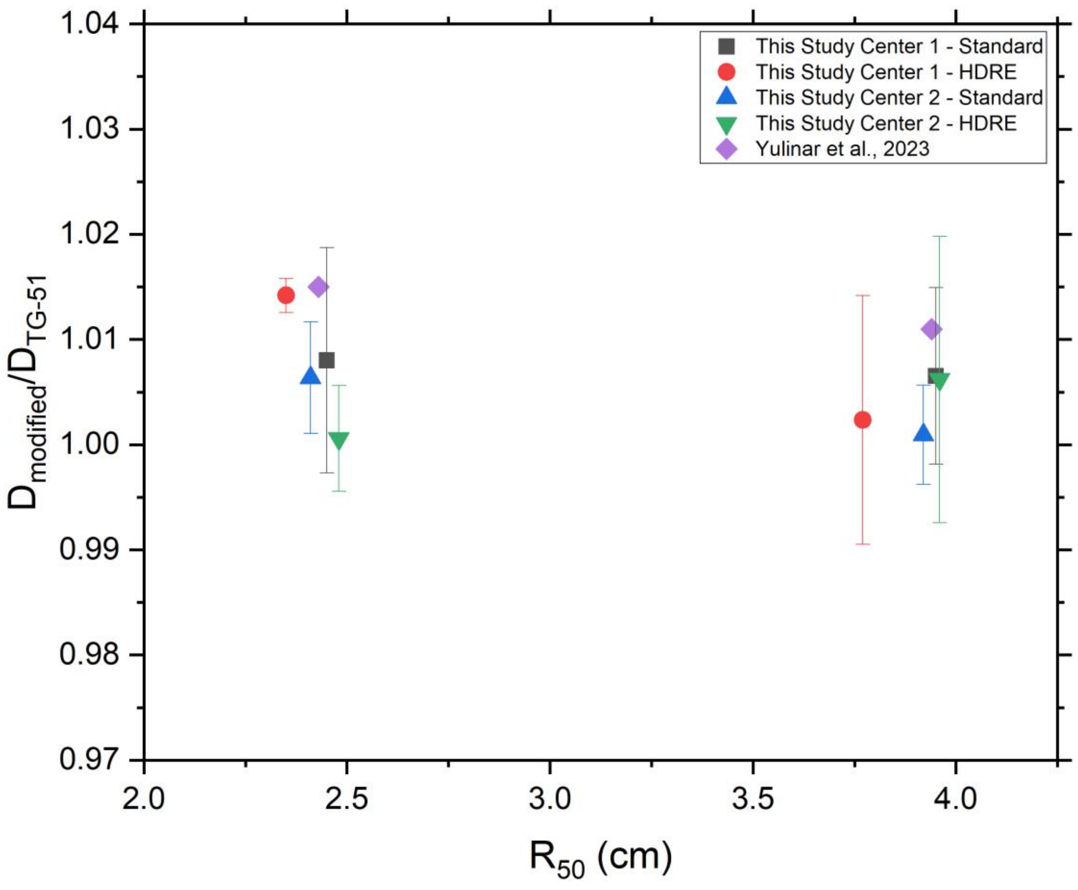
Cylindrical Detector: 0,999 – 1,006

Plan Parallel Detector: : 0,998 – 1,003

Absorbed Dose Ratio



Absorbed Dose ratio: TRS 398 versus Modified



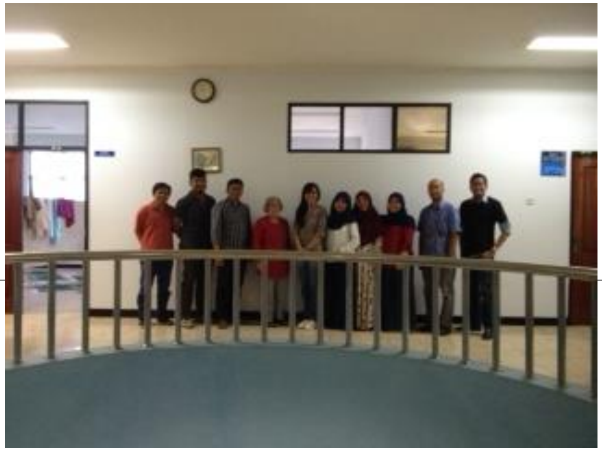
Absorbed Dose ratio: AAPM TG51 versus Modified

Conclusion

01 Ion Recombination electron beam P_{ion} for mode HDRE higher than conventional electron beam : PTW 30013, PTW Roos, IBA FC65P, IBA CC13 dan IBA PPC40 is 0 5,00 – 5,33 %, 4,52 – 5,06 %, 3,22 – 3,51 %, 2,88 – 3,04 % dan 0,77 – 0,87%.

02 Quality beam Factor at IAEA TRS-398 have k_Q < 1,00 whereas k_Q > 1,00 for AAPM TG-51 and modified procedure

03 Deviation standard D/MU for all protocol/procedure in HDRE and conventional electron beam is below tolerance level ± 2%



Terima Kasih ★ Thank You

TUT WURI HANDAYANI

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