ALARA in a *FLASH* – Radiation Shielding and Safety Implications Following Linac Conversion to An Electron *FLASH*-RT Unit

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INTRODUCTION

Due to their finite range, electrons are typically an afterthought in radiation safety. Although bremsstrahlung in the scattering foil creates significant dose that penetrates the radiation shielding when operated at *FLASH*-RT dose rates, its consequences on considerations for radiation shielding have yet to be investigated.

AIM

To investigate the implications of converting a Linac to *FLASH*-RT on radiation shielding requirements and radiation safety.

METHOD

A Varian 21EX C-series linear accelerator was converted to deliver 16 MeV at *FLASH*-RT dose rates.

The increase in absorbed dose rate was measured in the bremsstrahlung tail of the electron beam using an CC04 pinpoint ionization chamber (IBA Dosimetry) and confirmed via Gafchromic EBT-XD film calibrated on the clinical 16 MeV energy. The energy, flatness and symmetry of the 16 MeV *FLASH*-RT electron beam was confirmed via IC Profiler (Standard Imaging) measurements performed at extended SSD.

Two tests were performed:

1) Shielding measurements using a 451P ion chamber survey meter (Fluke Biomedical Inovision) and a Wendi-2 FHT 762 neutron detector (ThermoFisher Scientific) to measure neutron dose at the location of highest dose rate in 3 locations:
   a. at the console,
   b. at the Linac door, and
   c. in the uncontrolled area above the vault (highest dose)

2) Neutron activation:

Operation at *FLASH*-RT dose rates produces neutron activation of Linac head components which may be in excess to that produced by 18 MV operation. Therefore, the equivalent dose rate within the vault following operation of *FLASH*-RT for 1.8 minutes was measured for 40 minutes using a 451P Inovision ion chamber survey meter in 3 locations: near the Linac head, at isocenter, and ~2m from the head.

RESULTS – RADIATION SURVEY

We measured an equivalent dose rate from FLASH-RT in an uncontrolled area which was ~70 times as high as that produced by the 18 MV beam for which the shielding was designed. At this measured ~800 µSv total dose rate, the federal 20 µSv exposure limit in any single hour to uncontrolled areas is exceeded after only 90s of operation within any one hour. While workloads for *FLASH*-RT irradiations are much lower than clinical Linacs, 90s can easily be reached when performing beam tuning, routine dosimetry and QA, or pre-study dosimetry.

Table 1: Radiation Survey Results (Federal Limit – 20 µSv/hr)

Energy	Equivalent Dose rate measured in location (µSv/hr)					
	Door		Console		Uncontrolled Area	
	Photons	Neutrons	Photons	Neutrons	Photons	Neutrons
18 MV Photons	28	36	1.6	2	6	83
16 MeV e^- (Clinical)	0.4	Not Detectable	0.2	Not Detectable	0.2	Not Detectable
16 MeV e^- (*FLASH*)	65	45	3	4	430	350

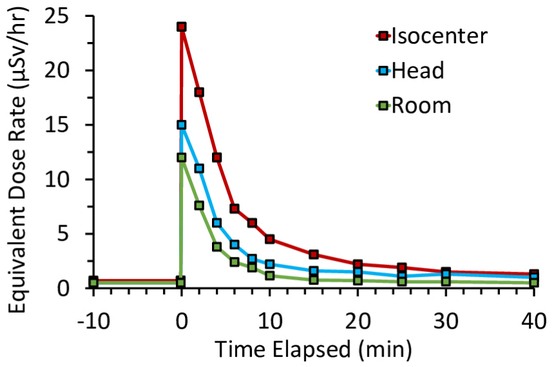
Furthermore, investigators converting their Linacs only proofed to 6 MV will face even greater dose rates in uncontrolled areas. These results show that proper consideration must be given to new conversion of Linacs to *FLASH*-RT dose rates.

RESULTS – LINAC HEAD NEUTRON ACTIVATION

The equivalent dose rate from activated component did originally exceed 10 µSv/hr, but this quickly dropped <10 µSv/hr within 5 minutes following the end of the FLASH-RT exposure.

Linac head activation is therefore only a significant issue for very long beam-on times necessitating immediate re-entry to the vault, which is unlikely to be an issue in converted FLASH-RT systems

Figure 1: Equivalent dose rate from activated Linac head components following *FLASH-RT*



RESULTS – LINAC *FLASH* CONVERSION

The 16 MeV electron beam has a bremsstrahlung efficiency of ~4%. The *FLASH*-RT mode which delivers dose at ~200× the clinical rate results in an instantaneous dose rate of ~15× the absorbed dose rate of an 18 MV photon beam due to bremsstrahlung photons alone.

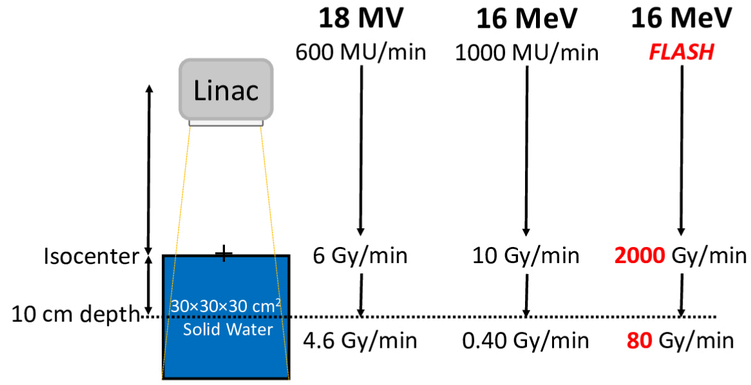


Figure 2: Conversion of 20 MeV electrons to 16 MeV *FLASH* dose rates

While the dose rate at isocenter is not quite capable of inducing *FLASH* effects, further improvement in dose rates are possible by reducing the source-to-surface distance by placing the samples on the faceplate (~110 Gy/s), within the Linac head at the level of the inner jaw (~218 Gy/s), at the level of the field-light indicator mirror (~655 Gy/s), or at the level of the monitor ion chamber (~2650 Gy/s).

CONCLUSIONS

While our Linac vault shielding proved sufficient for controlled areas, the equivalent dose rate in uncontrolled areas will exceed federal regulatory limits (20 µSv/hr) if operated for extended periods of time. Other investigators would be prudent to confirm the adequacy of their radiation safety program, particularly if operating in vaults only shielded for 6 MV photons.

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