



HAL
open science

First evidence of in vivo effect of FLASH radiotherapy with helium ions in zebrafish embryos

Youssef Ghannam, Sophie Chiavassa, Gaëlle Saade, Charbel Koumeir, Guillaume Blain, Grégory Delpon, Manon Evin, Ferid Haddad, Lydia Maigne, Quentin Mouchard, et al.

► To cite this version:

Youssef Ghannam, Sophie Chiavassa, Gaëlle Saade, Charbel Koumeir, Guillaume Blain, et al.. First evidence of in vivo effect of FLASH radiotherapy with helium ions in zebrafish embryos. *Radiotherapy Oncology*, 2023, 187, pp.109820. 10.1016/j.radonc.2023.109820 . hal-04201747

HAL Id: hal-04201747

<https://hal.science/hal-04201747>

Submitted on 19 Mar 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 **First evidence of in vivo effect of FLASH radiotherapy with helium ions in zebrafish**
2 **embryos**

3

4 Y. Ghannam^{1*}, S. Chiavassa^{2,3*}, G. Saade^{1*}, C. Koumeir^{2,4}, G. Blain², G. Delpon^{2,3}, M.
5 Evin², F. Haddad^{2,4}, L. Maigne⁵, Q. Mouchard², N. Servagent², V. Potiron^{1,3}, S. Supiot^{1,3}

6

7

8 **SUMMARY**

9 The ability to reduce toxicity of ultra-high dose rate (UHDR) helium ion irradiation has
10 not been reported *in vivo*. Here, we tested UHDR helium ion irradiation in an embryonic
11 zebrafish model. Our results show that UHDR helium ions spare body development and reduce
12 spine curvature, compared to conventional dose rate.

13

14 **INTRODUCTION**

15 One challenge of radiotherapy (RT) is to effectively treat tumors while preserving
16 healthy tissue. Preclinical evidence showed that UHDR radiotherapy selectively reduces the
17 toxicity to healthy tissues, but not to tumors, as compared to conventional dose rate
18 radiotherapy [1]. This "FLASH" effect, defined *in vivo per se*, has been mainly demonstrated
19 using electrons. Recent data suggest that it also occurs with protons and hadrons [2,3]. The
20 precise ballistics of the later turn helpful when facing volumetric dose constraints [4].
21 Combining this advantage with irradiation at UHDR is expected to further optimize the
22 benefit/risk ratio. One study tested the Flash effect with helium ions at UHDR assessing only
23 *in vitro* clonogenic survival [5]. However, there is currently no validation of helium ion UHDR-
24 RT in complex organisms. In this study, we compared the developmental response of zebrafish
25 embryos irradiated at UHDR or conv-DR using a helium ion beam.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21

MATERIAL AND METHODS

Helium ion beam and experimental setup

A monoenergetic ${}^4\text{He}^{2+}$ beam of 67.4 MeV was provided by the isochronous ARRONAX cyclotron (IBA Cyclone 70XP) [6] with a fixed micro-pulse frequency of 30.45 MHz. A homemade pulsing chopper-based system allowed macro-pulses of controlled duration ($>10\ \mu\text{s}$), frequency, and intensity [7]. This enabled conv-DR and UHDR in identical irradiation conditions. A 25 μm tungsten foil and two collimators ($\varnothing\ 15\ \text{mm}$) were used to spread and homogenise the beam (Fig. 1A). Dose distribution and beam energy were evaluated by numerical simulation with Monte Carlo GATE [8]. The mean energy at the entrance of the sample was estimated to be $40.3 \pm 2.3\ \text{MeV}$, leading to a Bragg peak depth of 1.24 mm (Fig. 1B). A plastic foil of 0.16mm was used to seal the wells and the embryos were maintained behind, on a single 1 mm thick layer (Fig. 1B and 1C). The mean Linear Energy Transfer (LET) inside the embryos was 27.6 keV/ μm . Mean delivered physical doses were $17.9 \pm 0.27\ \text{Gy}$ and $24.1 \pm 0.27\ \text{Gy}$ for UHDR and $18.0 \pm 0.36\ \text{Gy}$ and $24.0 \pm 0.29\ \text{Gy}$ for conv-DR. Considering a Relative Biological Effectiveness (RBE) between 1.5 to 2 [9], the theoretical biological doses were between 26.9 – 36.0 GyE and 36 – 48 GyE. A mean conv-DR of $0.25 \pm 0.02\ \text{Gy/s}$ and UHDR of $9.7 \pm 0.82\ \text{kGy/s}$ were applied. Beam structures, doses, online beam monitoring and dosimetry are presented in Table 1. Details on calculations are given in the Supplementary Material and Methods. Gray values (Gy) in the manuscript always refer to physical doses.

Zebrafish embryo culture and irradiation

Wildtype AB zebrafish (*Danio rerio*) eggs were provided at 1-hour post-fertilization (hpf) by the ImpACcell facility (Biosit, Univ. Rennes, France). Embryos were transported and cultured at 28°C in E3 medium. One hour prior to irradiation delivered at 28 hpf, 32 eggs were

1 placed as a single layer in 100 μ l (Fig. 1C). Viability rates were calculated on the 4th day
2 relatively to the number of surviving embryos 1 hour after irradiation. At 5 days post-
3 fertilization (dpf), cold-anesthetized embryos were fixed with 4% formol and later
4 photographed with a Ni-U stand and 2X objective with 0.06 numerical aperture (Nikon
5 Instruments, Melville, USA). The length (a) of embryos was measured by drawing along the
6 vertebral column using Fiji software (ImageJ 1.53q). The Euclidean distance (b) was measured
7 by a straight line from the tip of the head to end of the tail. Curvature represents the a/b ratio.
8 Pericardial edema was scored as reported [10]. The toxicity reduction was calculated
9 normalized to the conv-DR effect with the formula: $100 * [1 - ((\text{ctl value} - \text{UHDR value}) / (\text{ctl}$
10 $\text{value} - \text{conv-DR value}))]$.

11 *Statistical analysis*

12 Three independent experiments (egg batch, beam, date) were performed to ensure
13 reproducibility. GraphPad Prism (Version 6) was used for statistical analysis. Mean survival
14 rates were tested with Kruskal-Wallis followed by Dunn's correction. Mean values of the
15 length, curvature and pericardial edema were compared using a One-way Anova test followed
16 by Bonferroni correction. For all figures, compiled data are presented \pm sd with * = $p < 0.05$; **
17 = $p < 0.01$; *** = $p < 0.001$; **** = $p < 0.0001$.

18 19 **RESULTS**

20
21 To investigate the effect of UHDR $^4\text{He}^{2+}$ ions, a homogeneous beam with real-time
22 dosimetric control was designed at the Arronax cyclotron (Fig. 1A) for irradiating a ≤ 1 mm
23 thick target in the plateau (Fig. 1B). Zebrafish embryos of 1240 μ m at 28 hpf were aligned
24 vertically on the same plane using home-made well insert (Fig. 1C). Development and
25 morphology of zebrafish embryos were measured after conv-DR and UHDR irradiations. As
26 expected, viability of non-irradiated controls was close to 100% (Fig. 2A). No statistical

1 difference was found between conv-DR and UHDR either at 18 Gy ($87\% \pm 5$ vs $94\% \pm 5$) or at
2 24 Gy ($80\% \pm 14$ vs $90\% \pm 8$) (Fig. 2A). At 4 days post-irradiation, zebrafish embryos irradiated
3 with 18 Gy UHDR had longer body length ($3025 \pm 227 \mu\text{m}$) compared to those irradiated with
4 conv-DR ($2937 \pm 252 \mu\text{m}$, $p < 0.001$) (Fig. 2B). Similar results were found at 24 Gy (2925 ± 219
5 μm vs $2830 \pm 288 \mu\text{m}$, $p < 0.0001$) (Fig. 2B). This represented a toxicity reduction by 15% at 18
6 Gy and 14% at 24 Gy. Notably, embryos exposed to 24 Gy UHDR were as long as those
7 exposed to 18 Gy conv-DR.

8 Embryos irradiated with both modalities developed a spine curvature, in opposite to
9 controls. A significant reduction of the curvature ratio was observed at 24 Gy UHDR compared
10 to conv-DR (1.10 ± 0.19 vs 1.20 ± 0.43 , $p < 0.01$), although not at 18 Gy ($p > 0.05$) (Fig. 3A).
11 Similarly, pericardial edema was observed after RT but not in controls (Fig. 3B). The severity
12 of edema was less important at 24 Gy ($p < 0.05$) after UHDR (score = 2.65 ± 0.79) compared to
13 conv-DR (score = 2.84 ± 0.87 ; (Fig. 3B).

14 15 **DISCUSSION** 16

17 The UHDR-mediated reduced toxicity has been demonstrated in various model
18 organisms. With the zebrafish embryo model, protection in body length, pericardial edema or
19 spinal curvature has been validated with electrons and protons, although not consistently [11-
20 13]. Recent results from our laboratory confirmed a reduced toxicity of protons at UHDR [14].
21 However, to our knowledge, no data has been published for helium ions *in vivo*.

22 The biological response to UHDR helium ion beams has been reported in human cancer
23 cell lines *in vitro* with higher clonogenic survival only under 1% O₂ [5]. The present study
24 shows for the first time the protective effect of UHDR helium ions *in vivo*. These results are
25 consistent with our previous experiments using protons at similar beam energy and dose rates,
26 leading to the same magnitude of protection by UHDR (toxicity reduction of protons: 9-20%

1 helium ions: 14-15%). It is nevertheless difficult to provide definitive conclusions regarding
2 the biological doses, with effects of -25% to -28% in body size with conv-DR protons [14] and
3 of -17% to -20% here. The present data fit better with a RBE in the lower estimated range, of
4 ≈ 1.5 . Some level of variability likely rises from varying orientation of the embryos and local
5 oxygen gradients. The differential between conv-DR and UHDR lies between 100-200 μm ,
6 which is mostly in agreement with data from Beyreuther's group but not comparable with other
7 studies performed at 4 hpf. Interestingly, helium ions are heavier particles than protons,
8 resulting in higher linear energy transfer. High LET values are supposed to induce more
9 efficient cell destruction, accompanied by reduced hypoxia dependence. Yet, the impact of the
10 pO₂ on the FLASH effect in zebrafish has been demonstrated [13,15]. Our preliminary
11 measurements suggest that eggs in our proton setup were more hypoxic (0-5 mm Hg) than those
12 in the current helium setup (≈ 30 mm Hg). Therefore, it would be interesting in future studies
13 to perform experiments with helium ion beams in controlled O₂ environments in order to
14 elucidate this apparent paradox.

15
16 **CONCLUSION**

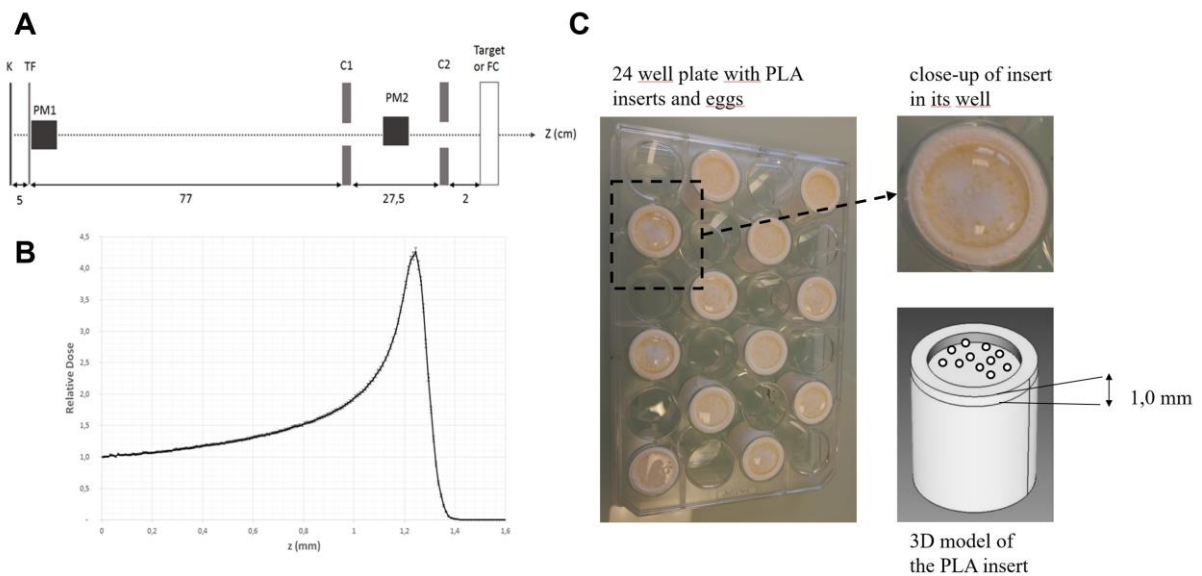
17
18 This study shows for the first time the *in vivo* effect of a UHDR helium ion beam. These
19 findings advocate for the validity of combining high LET ion beams with the UHDR modality
20 to benefit from both good ballistics and reduced toxicity.

21

Experiment	Macro-pulse Dose rate (Gy/s)	Mean Dose rate (Gy/s)	Macro-pulse width (ms)	Macro-pulse Frequency (Hz)	Number of macro-pulses	Total beam on time (ms)	Mean physical dose at the embryos (Gy)
FLASH day 1	7065	7065	2.05	-	1	2.05	14.8
	7255	7255	2.05			15.2	
	7136	7136	2.74			20.0	
	7052	7052	2.74			19.7	
CONV day 1	7.23	0.23	1.1	28.6	1914	67 E+3	15.2
	7.03	0.22			1914	67 E+3	14.8
	7.23	0.23			2514	88 E+3	20.0
	6.85	0.22			2629	92 E+3	19.8
FLASH day 2	7734	7734	1.95	-	1	1.95	15.1
	7643	7643	1.92			14.7	
	7758	7758	2.60			20.2	
	7803	7803	2.60			20.3	
CONV day 2	4.9	0.21	1.5	28.6	2029	71 E+3	15.0
	5.4	0.23			1829	64 E+3	14.7
	5.1	0.22			2571	90 E+3	19.9
	5.6	0.24			2457	86 E+3	20.5

1

2 **Table1. Beam structures and doses for conv-DR and UHDR irradiations.**



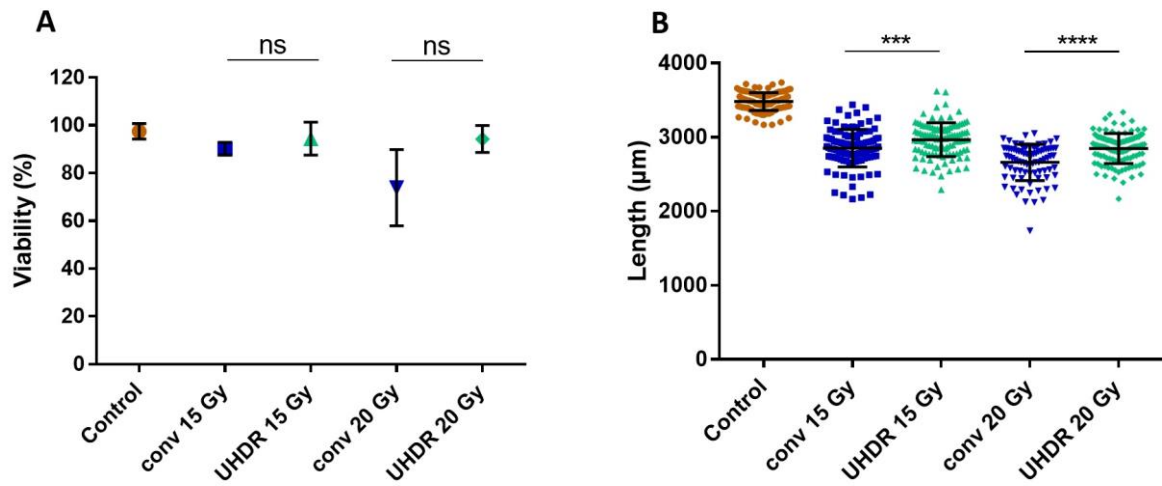
3

4 **Figure 1. Helium ion beam experimental setup.**

5 **A** Beam path with the exit kapton window (K), the tungsten foil (TF), the first collimator (C1),
6 the photomultiplier tubes (PM1 and PM2), the second collimator (C2) and the Faraday cup
7 (FC). Distances are in cm. **B** Bragg peak of the helium ion beam at the target level simulated in

1 water with GATE v9.0 [8]. The gray zone corresponds to the adhesive plastic foil for closing
2 wells. **C** Zebrafish embryo positioning in the experimental target plate.

3



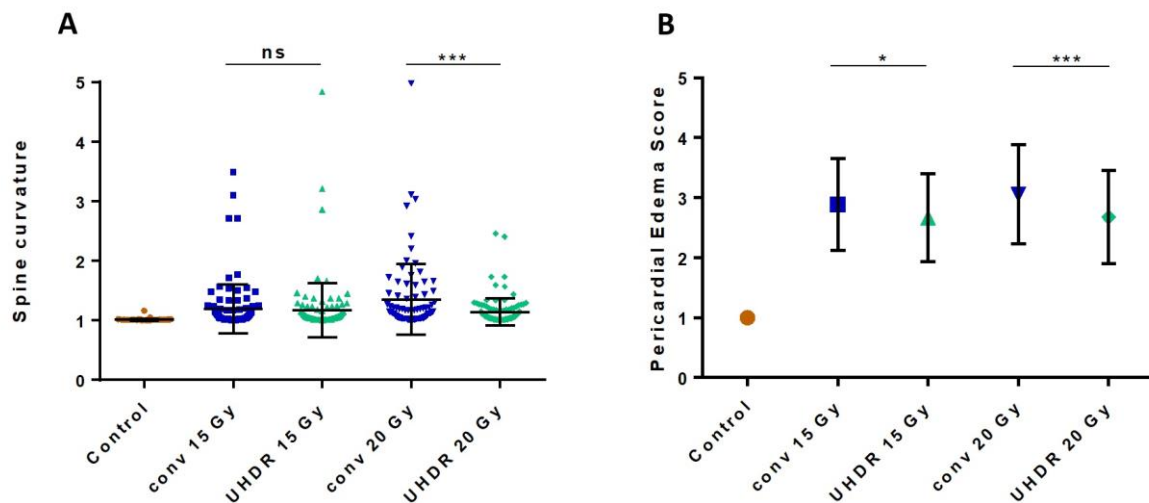
4

5

6 **Figure 2. Effect of UHDR ⁴He²⁺ irradiation on zebrafish embryo growth.**

7 Embryos were irradiated at 28 hpf. **A** Viability rate at 4 dpf. **B** Body length at 5 dpf. n= indicates
8 the number of embryos per point.

9



10

11

12 **Figure 3. Effect of UHDR ⁴He²⁺ irradiation on zebrafish embryo morphology.**

1 Embryos were irradiated at 28 hpf. **A** Spinal curvature (length/Euclidean distance ratio). **B**
2 Pericardial edema score. n= indicates the number of embryos per point.

3

4 **Acknowledgements:**

5 The GIP ARRONAX is supported by CNRS, Inserm, INCa, the Nantes Université, the Regional
6 Council of Pays de la Loire, local authorities, the French government and the European Union.

7 This project is partially supported by grants from the French National Agency for Research
8 called “Investissements d’Avenir”, Equipex Arronax-Plus (ANR-11- EQPX-0004) and ISITE

9 NExT (ANR-16-IDEX-0007). This work was financially supported by Inserm Cancer, La Ligue
10 contre le Cancer, Institut de Cancérologie de l’Ouest and IRC Transformed. We thank the x-per

11 facility, Institut de Cancérologie de l’Ouest, for pilot experiments. We thank the ImPACcell
12 facility, Univ. Rennes 1, for zebrafish housing and technical help.

13

14 **References**

15

16 [1] Favaudon V, Caplier L, Monceau V, et al. Ultrahigh dose-rate FLASH irradiation
17 increases the differential response between normal and tumor tissue in mice. *Sci*
18 *Transl Med.* 2014;6(245):245ra93-245ra93. doi:10.1126/scitranslmed.3008973

19 [2] Diffenderfer ES, Sørensen BS, Mazal A, Carlson DJ. The current status of preclinical
20 proton FLASH radiation and future directions. *Med Phys.* 2022 Mar;49(3):2039-
21 2054. doi: 10.1002/mp.15276. Epub 2021 Oct 26.

22 [3] Tinganelli W, Sokol O, Quartieri M, Puspitasari A, Dokic I, Abdollahi A, Durante
23 M, Haberer T, Debus J, Boscolo D, Voss B, Brons S, Schuy C, Horst F, Weber U.
24 Ultra-High Dose Rate (FLASH) Carbon Ion Irradiation: Dosimetry and First Cell
25 Experiments. *Int J Radiat Oncol Biol Phys.* 2022 Mar 15;112(4):1012-1022. doi:
26 10.1016/j.ijrobp.2021.11.020. Epub 2021 Nov 20.

27 [4] Jäkel O. Physical advantages of particles: protons and light ions. *Br J Radiol* 2020;
28 93: 20190428.

29 [5] Tessonnier T, Mein S, Walsh D, et al. FLASH dose-rate helium ion beams: first *in*
30 *vitro* investigations. *International Journal of Radiation Oncology, Biology, Physics*
31 (2021), doi: <https://doi.org/10.1016/j.ijrobp.2021.07.1703>

32 [6] Koumeir C, De Nadal V, Cherubini R, et al. The radiobiological platform at arronax.
33 *Radiat Prot Dosimetry.* 2019;183(1-2):270- 273. <https://doi.org/10.1093/rpd/ncy301>

34 [7] Poirier F, Blain G, Bulteau-Harel F, et al. The injection and chopper-based system at
35 Arronax C70XP cyclotron. In: *Proceedings of the 22nd International Conference on*
36 *Cyclotrons and Their Applications, Cyclotrons2019.* 2020. [https://doi.org/10.](https://doi.org/10.18429/JACOW-CYCLOTRONS2019-TUP006)
37 [18429/JACOW-CYCLOTRONS2019-TUP006](https://doi.org/10.18429/JACOW-CYCLOTRONS2019-TUP006)

- 1 [8] Sarrut D, Bardiès M, Bousson N, et al. A review of the use and potential of the
2 GATE Monte Carlo simulation code for radiation therapy and dosimetry
3 applications. *Med Phys.* 2014;41(6):064301. doi:10.1118/1.487161
- 4 [9] Mein S, Dokic I, Klein C, *et al.* Biophysical modeling and experimental validation
5 of relative biological effectiveness (RBE) for 4 He ion beam therapy. *Radiation*
6 *Oncology*, 2019, vol. 14, no 1, p. 1-16.
- 7 [10] Szabó ER, Brand M, Hans S, et al. Radiobiological effects and proton RBE
8 determined by wildtype zebrafish embryos. *PLOS ONE.* 2018;13(11):e0206879.
9 doi:10.1371/journal.pone.0206879
- 10 [11] Vozenin MC, Hendry JH, Limoli CL. Biological Benefits of Ultra-high Dose Rate
11 FLASH Radiotherapy: Sleeping Beauty Awoken. *Clin Oncol R Coll Radiol G B.*
12 2019;31(7):407-415. doi:10.1016/j.clon.2019.04.001
- 13 [12] Kacem H, Psoroulas S, Boivin G, et al. Comparing radiolytic production of H₂O₂
14 and development of Zebrafish embryos after ultra high dose rate exposure with
15 electron and transmission proton beams. *Radiother Oncol.* 2022 Jul 19:S0167-
16 8140(22)04207-4. doi: 10.1016/j.radonc.2022.07.011.
- 17 [13] Karsch L, Pawelke J, Brand M, et al. Beam pulse structure and dose rate as
18 determinants for the flash effect observed in zebrafish embryo. *Radiother Oncol.*
19 2022;173:49-54. doi:10.1016/j.radonc.2022.05.025
- 20 [14] Saade G, Bogaerts E, Chiavassa S et al. Ultra-high dose rate proton irradiation elicits
21 reduced toxicity in zebrafish embryos. *Adv Rad Onc*, in press.
- 22 [15] Pawelke J, Brand M, Hans S, et al. Electron dose rate and oxygen depletion protect
23 zebrafish embryos from radiation damage. *Radiother Oncol.* 2021;158:7-12.
24 doi:10.1016/j.radonc.2021.02.003
25
26
27