Online Anomaly Detection using Radiation Acoustic Imaging (iRAI) in Conventional and FLASH Proton Radiotherapy

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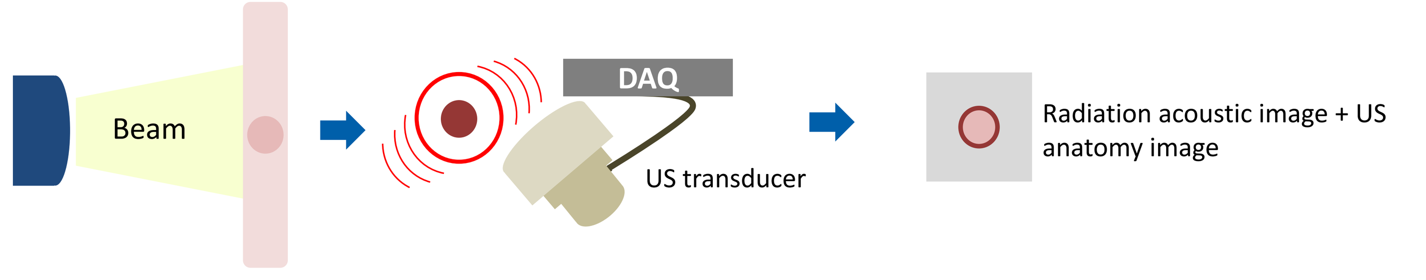
Background & Motivation

1. High precision is critical in modern RT, especially Ultra-high Dose Rate (UHDR) or FLASH radiotherapy.
2. Small delivery deviations may cause major clinical impact.
3. Current verification techniques are retrospective, not truly online.
4. **Need for fast, automated real-time dose monitoring.**

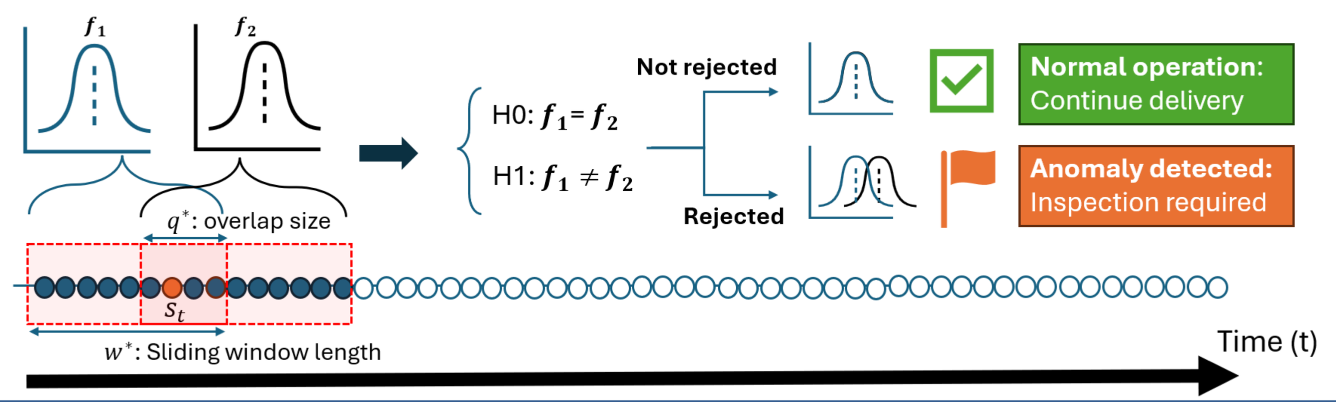
Ionizing radiation-induced acoustic imaging (iRAI)

1. Acoustic wave generated by thermal-acoustic effect during irradiation can be detected by acoustic transducers.
2. Initial acoustic pressure can be reconstructed from detected signal.



Methods & Materials

- A novel **anomaly detection is proposed** for **in-treatment** detection of unexpected beam delivery, using signal processing and statistical anomaly detection for on-fly analysis of iRAI signals.
- Anomaly detection works by comparing expected signal morphology (from simulations) with the observed iRAI signals, flagging "anomalies" as significant shifts in the observed 1-D and 2-D distributions.
- **Experiment 1 (Protons):** Acquired iRAI signals during conventional and UHDR proton beam delivery while varying beam energy, current, and transducer position relative to the Bragg peak.
- **Experiment 2 (Electrons):** Acquired iRAI signals during UHDR electron beam delivery using phantoms with and without an air-equivalent (Styrofoam) inclusion to simulate a treatment anomaly across different field sizes.



Results & Key Findings

- **Experiment 1 (Protons): The anomaly detection framework achieved 93% detection accuracy (25/27 paired experiments) while distinguishing normal from anomalous deliveries across variations in beam energy, beam current, and transducer distance to the Bragg peak.**
- **Experiment 2 (Electrons): The framework achieved 100% detection accuracy (48/48 paired experiments) across varying field sizes and simulated air-equivalent treatment anomalies (Styrofoam inclusion at different phantom locations).**

Experimental setup (conventional proton beam)

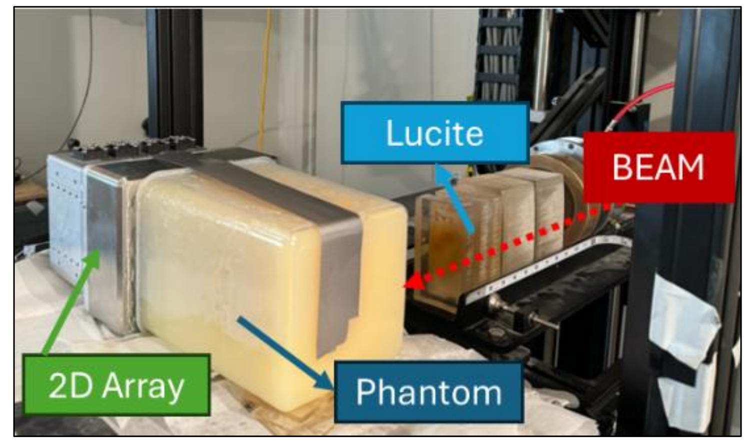


Fig. 1. Experimental setup under conventional proton: Acoustic (iRAI)-based dose monitoring in an oil phantom

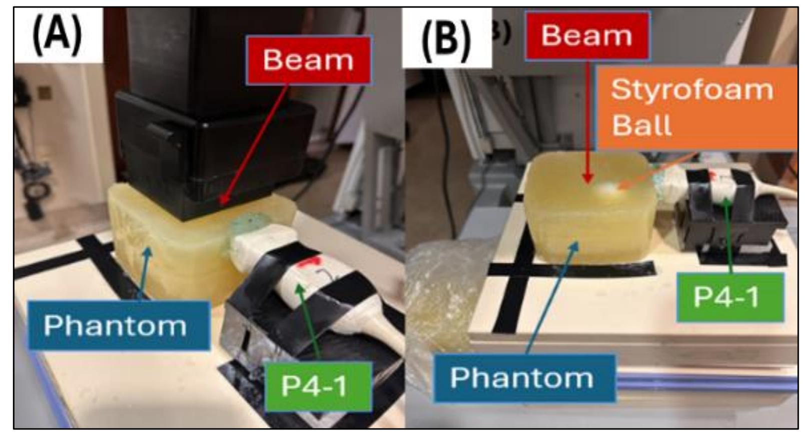


Fig. 2. (A) Experimental setup under UHDR Linac (electron); (B) Second Oil Phantom with Styrofoam ball;.

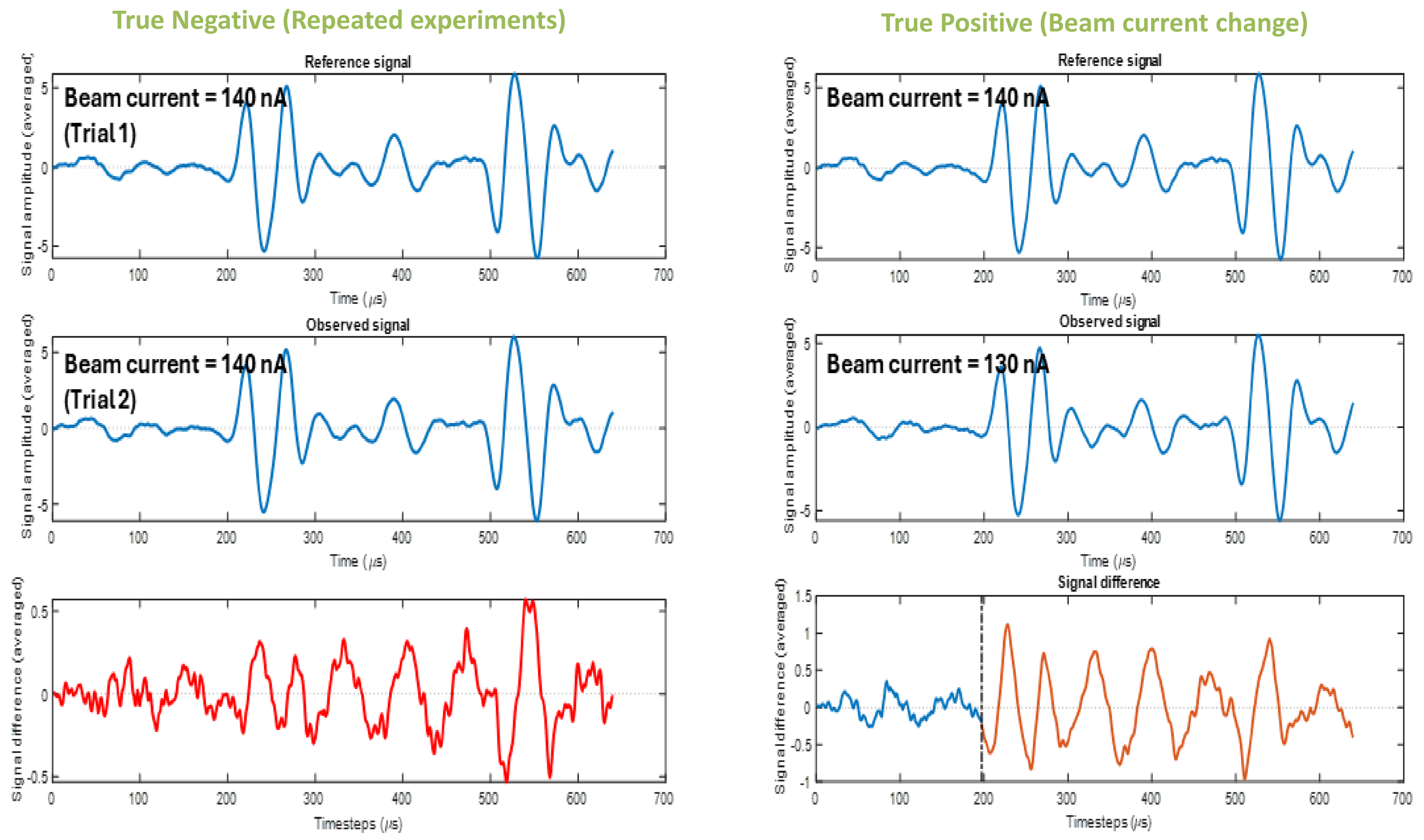


Fig. 2. Anomaly detection on conventional proton setup: identical repeated experiments using the same beam current (left) and decreased beam current (140 vs. 130 nA) detected by the algorithm. Overall, 25/27 (93%) beam signal alterations were automatically detected by the algorithm under Setup 1.

Experimental setup (electron FLASH)

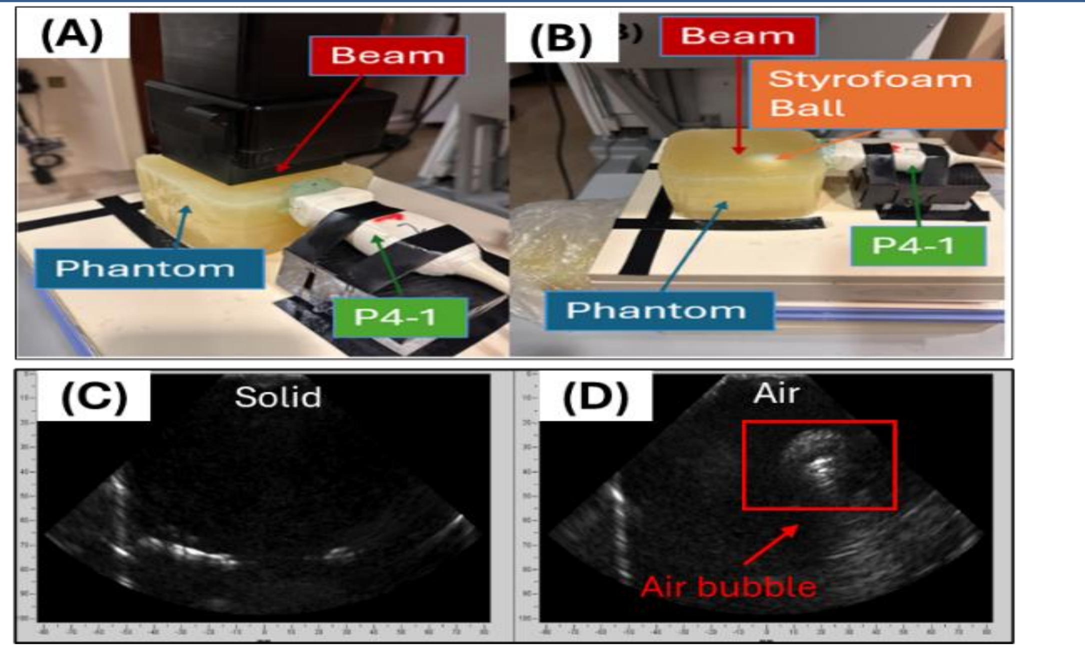


Fig. 3. (A) Experimental setup under UHDR Linac; (B) Second Oil Phantom with Styrofoam ball; (C-D) Ultrasound images from P4-1 without (C) and with (D) air bubbles.

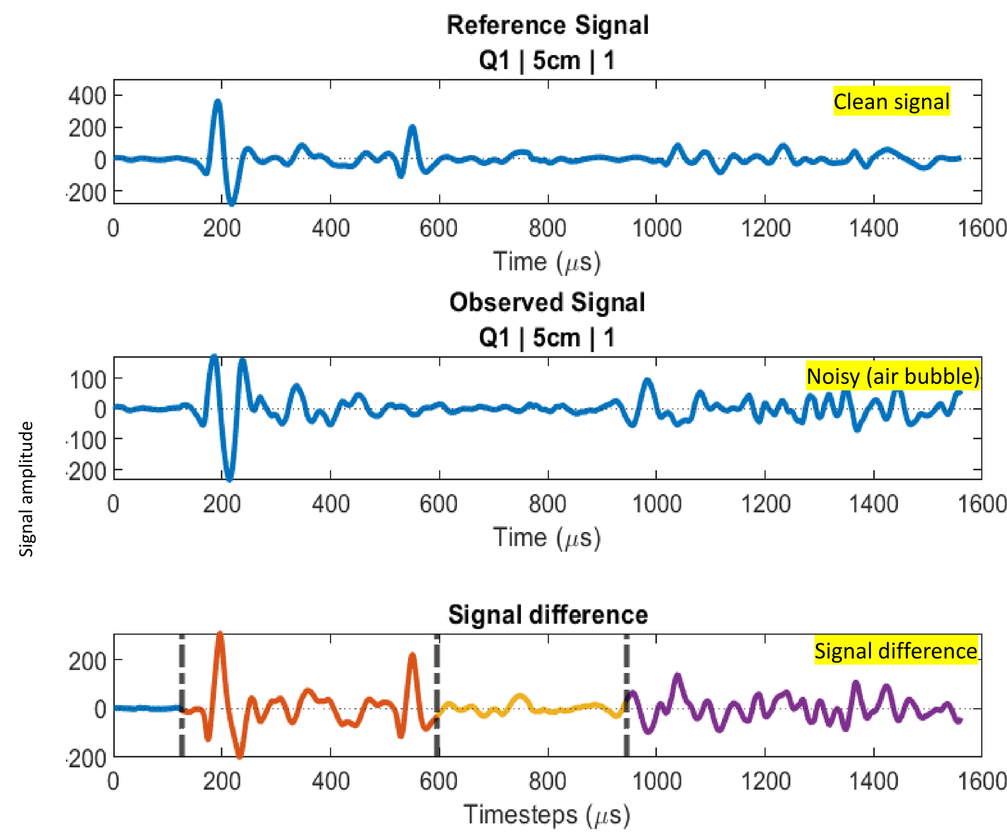


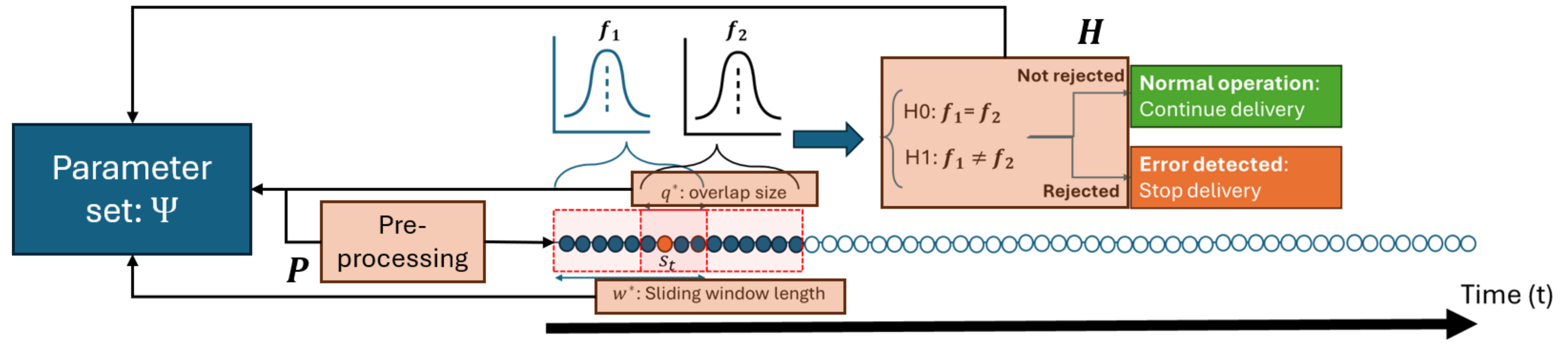
Figure 3. (A) Experimental setup under UHDR Linac; (B) Second Oil Phantom with Styrofoam ball; (C-D) Ultrasound images from P4-1 without (C) and with (D) air bubbles; (E) Corresponding iRAI signal in solid oil (reference) and in oil with "air bubble" (observed) and the signal deviations determined by the AD algorithm. 48/48 (100%) air bubble disruptions were detected by the AD algorithm.

Ongoing Works: Optimal parameterization of the algorithm

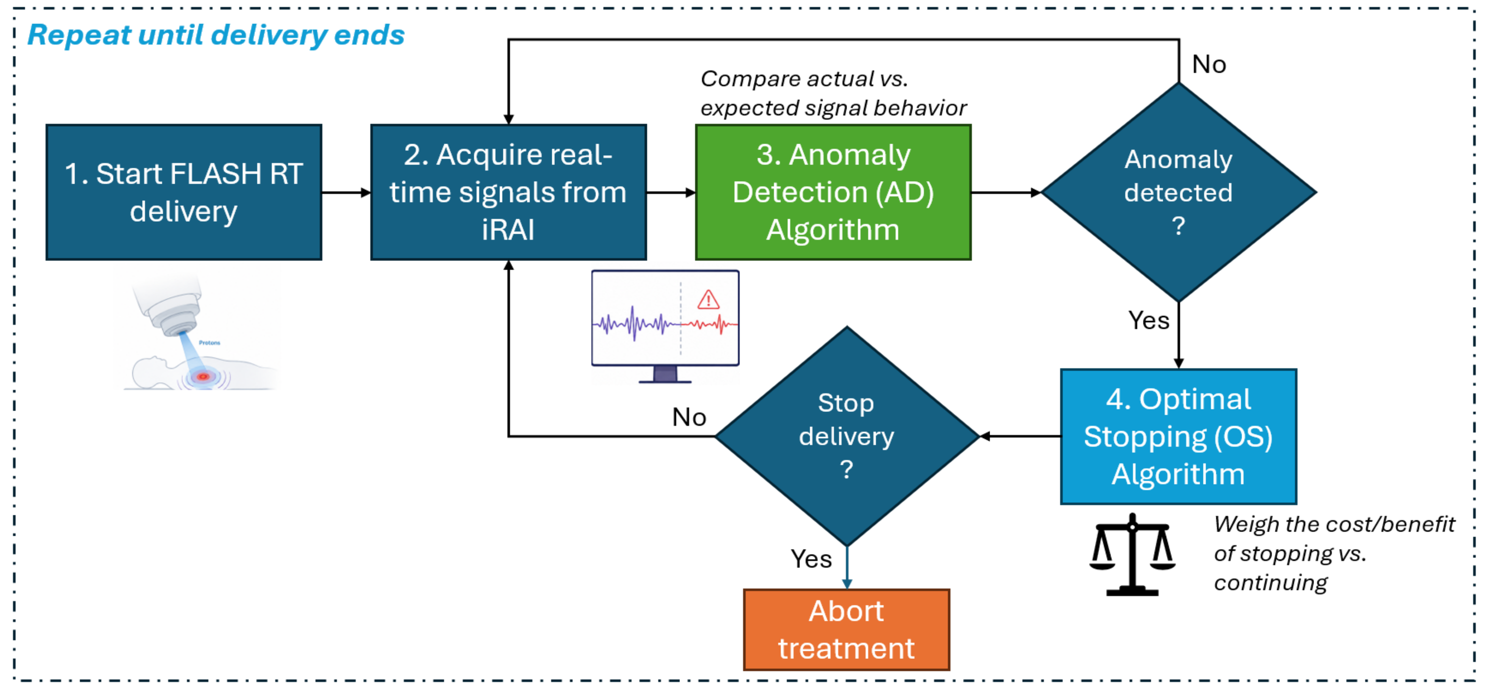
- AD parameters $\Psi = (\boldsymbol{w}, \boldsymbol{q}, \boldsymbol{H}, \boldsymbol{P})$ could be optimized to minimize an overall cost/loss function (e.g., false positive/negative rate).
- **Optimize Ψ** to fit the experiment/desired sensitivity:

$$\Psi^* = \mathrm{argmin}_{\Psi}\, \mathcal{L}(\Psi, s, s', \mathbf{y})$$

where **y** is a binarized/continuous dosimetric anomaly.



Combining Anomaly Detection with Optimal Stopping



Conclusions

- A **fast and fully automatic** method for detecting incidental errors in RT dose delivery using **anomaly detection** techniques, enabling **online dose verification and error detection** in advanced, high-stake proton RT.
- Algorithm's sensitivity can be fine-tuned depending on the task to weigh the benefit vs. cost of early stopping:
  - Preventing "off-target" delivery & Protecting normal tissue, vs.
  - Losing flash effect & disrupted delivery (dosimetrically, biologically, and psychologically)

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References

1. Zhang, W. et al. Real-time, volumetric imaging of radiation dose delivery deep into the liver during cancer treatment. Nature Biotechnology 2023 41:8 41, 1160–1167 (2023).
2. Oraiqat, I. et al. An Ionizing Radiation Acoustic Imaging (iRAI) Technique for Real-Time Dosimetric Measurements for FLASH Radiotherapy. Med Phys 47, 5090 (2020).
3. Verzelen, N., Fromont, M., Lerasle, M. & Reynaud-Bouret, P. Optimal Change-Point Detection and Localization. Ann Stat 51, 1586–1610 (2020).