JOINT ICTP-IAEA WORKSHOP ON RADIATION PROTECTION IN IMAGE-GUIDED RADIOTHERAPY (IGRT)

Rationale for Adaptive Radiotherapy

Sebastien Gros, PhD, DABR, FAAPM
Radiation Oncology Department
Stritch School of Medicine
ICRP TG-116 Member, Former Mentee

LOYOLA
UNIVERSITY CHICAGO

Outline

Introduction to Adaptive Radiation Therapy
Challenges in Conventional Radiotherapy
Benefits of Adaptive Radiotherapy
When and Why to Adapt?
Technological Advancements Enabling ART
Current Clinical Practices
Challenges and Limitations
Conclusions

INTRODUCTION TO ADAPTIVE RADIOTHERAPY

Introduction to Adaptive Radiotherapy

ART is a method that allows modifications to the radiotherapy treatment plan during the course of treatment.

- **Dynamic Approach**: Unlike conventional static plans, ART can adjust to anatomical or biological changes in the patient that occur over time.

Introduction to Adaptive Radiotherapy

Why ART is Needed:

- **Changing Anatomy**: During treatment, patient anatomy can change (e.g., weight loss, tumor shrinkage). These changes can affect the accuracy of radiation delivery if the treatment plan is not adjusted.

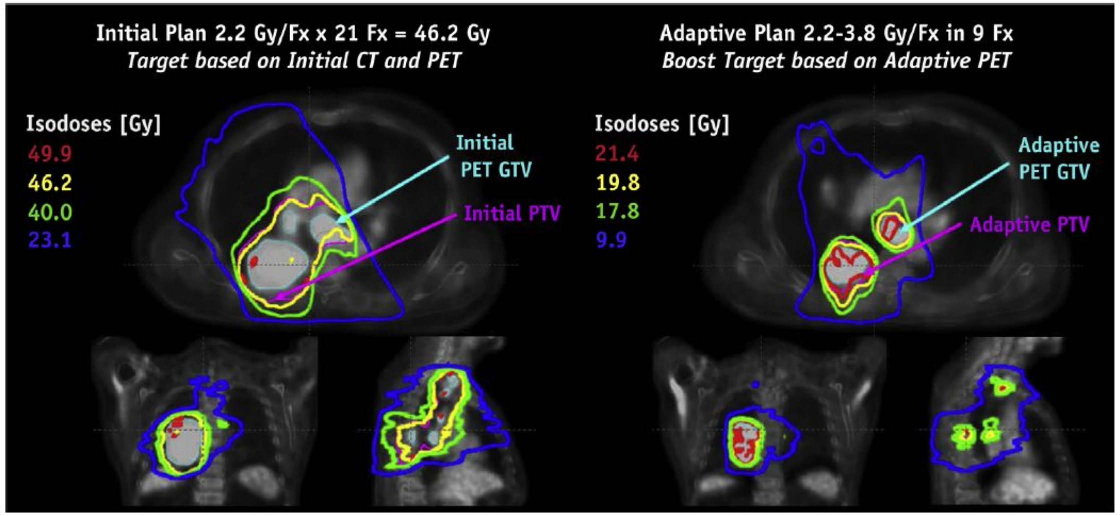
- **Impact on Treatment**: Static treatment plans may lead to underdosing the tumor or overdosing healthy tissues, reducing the effectiveness of the therapy and increasing side effects.

Introduction to Adaptive Radiotherapy

Purpose of ART:

- **Adapting in Real-Time**: ART allows for ongoing adjustments to the treatment plan, ensuring it stays aligned with the patient's changing anatomy and biological conditions.

- **Improving Outcomes**: By adapting the plan during treatment, ART improves tumor control and reduces unnecessary radiation to healthy tissues, thus minimizing side effects.



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ART is a solution to the inherent limitations of static treatment plans in conventional radiotherapy.

CHALLENGES IN CONVENTIONAL RADIOTHERAPY

Challenges in Conventional Radiotherapy

Static Treatment Plans:

- **Fixed Plan**: Conventional radiotherapy relies on a treatment plan created at the start of therapy, which remains unchanged throughout the treatment course.
- **Assumes Constant Anatomy**: The static plan assumes that the patient’s anatomy remains unchanged during treatment, which is often not the case.

Challenges in Conventional Radiotherapy

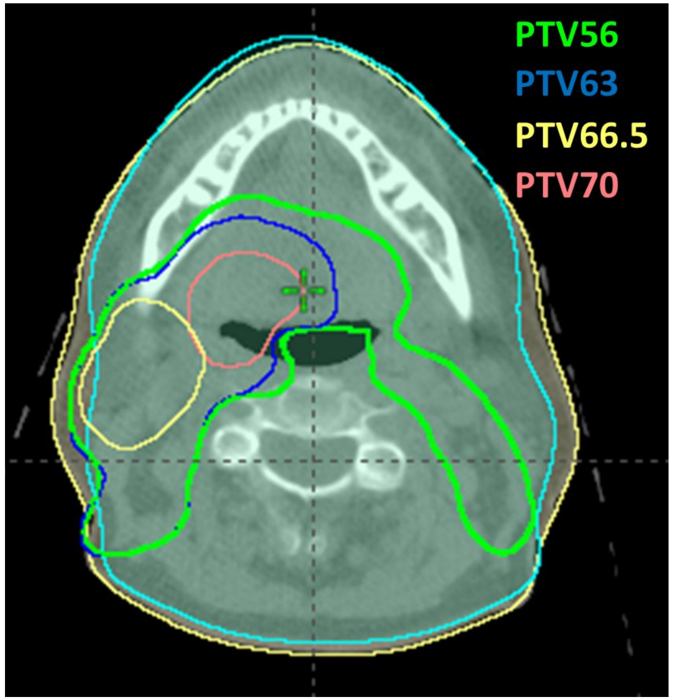
Common Anatomical Changes During Treatment:

Tumor Response:

- ***Shrinkage***: as the tumor responds to radiation, it may shrink. This can result in the radiation missing part of the tumor if the plan isn't adjusted
- ***Progression***: RT doesn't work as intended and the tumor grows

Weight Loss or Organ Movement:

Changes like weight loss or shifts in nearby organs (e.g., bladder, rectum, or stomach filling) can cause the tumor to move relative to the original plan.

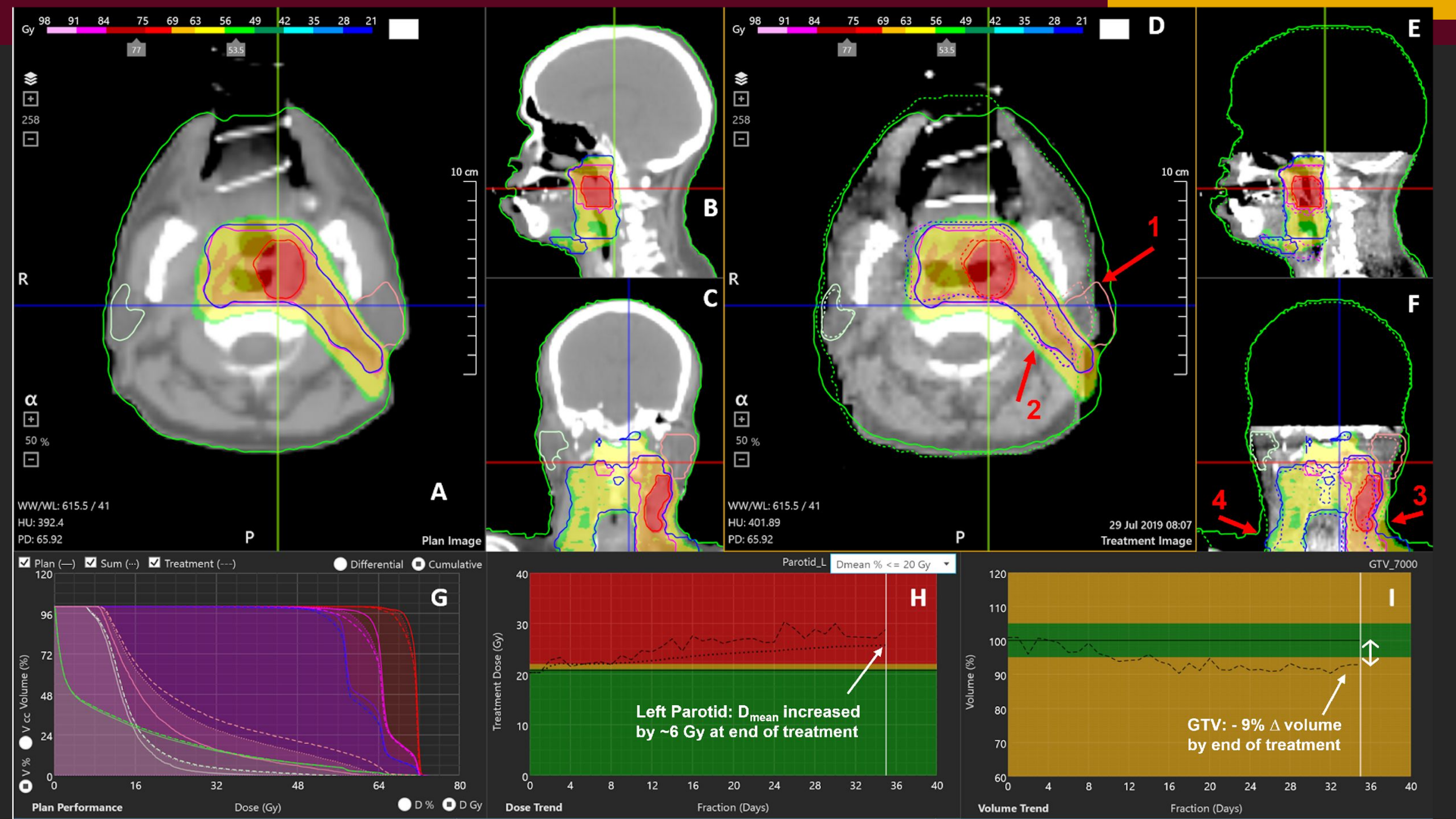


Challenges in Conventional Radiotherapy

Resulting Issues from Static Plans:

- **Missed Target**: Without adjustment, the radiation beam may no longer align with the tumor, reducing the effectiveness of the treatment.
- **Damage to Healthy Tissues**: If nearby organs or tissues shift, they may receive unintended radiation, leading to increased side effects or complications.
- **Compromised Tumor Control**: Underdosing the tumor can lead to less effective treatment, increasing the chances of recurrence or failure.

Relying on a single, unchanging treatment plan can lead to suboptimal outcomes.



A
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1
2
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Plan Image
Treatment Image
29 Jul 2019 08:07
WW/WL: 615.5 / 41
HU: 392.4
PD: 65.92
HU: 401.89
10 cm
Plan (—) Sum (···) Treatment (---)
Differential Cumulative
Plan Performance
Dose (Gy)
Volume (%)
Parotid_L
Dmean % <= 20 Gy
Treatment Dose (Gy)
Left Parotid: D mean increased by ~6 Gy at end of treatment
Dose Trend
Fraction (Days)
GTV_7000
GTV: - 9% Δ volume by end of treatment
Volume Trend

BENEFITS OF ADAPTIVE RADIOTHERAPY

Benefits of Adaptive Radiotherapy

Increased Precision:

- **Plan Adjustments**: ART allows the treatment plan to be modified based on real-time or frequent imaging, ensuring the radiation precisely targets the tumor despite anatomical changes.

- **Improved Accuracy**: This dynamic adjustment reduces the chance of misalignment between the radiation beam and the tumor, enhancing the precision of dose delivery.

Benefits of Adaptive Radiotherapy

Reduction in Toxicity:

- **Sparing Healthy Tissue**: By continually adapting the treatment plan, ART reduces unnecessary radiation exposure to surrounding healthy tissues and critical organs, lowering the risk of side effects.

- **Organ Motion Compensation**: ART accounts for shifts in organs near the tumor (e.g., bladder, bowel) that could otherwise receive unintended doses of radiation.

Benefits of Adaptive Radiotherapy

Improved Tumor Control:

- **Maintaining Full Dose to Tumor**: ART ensures the tumor receives the full prescribed dose of radiation, even as its size or position changes. This improves the chances of successfully controlling or eliminating the tumor.

- **Consistent Targeting**: As the tumor shrinks or shifts during the course of treatment, ART keeps the radiation field aligned with the tumor, improving the overall efficacy of the treatment.

ART offers precision, reduced toxicity, and improved tumor control by adapting to changes in the patient's anatomy during treatment.

WHEN AND WHY TO ADAPT?

When and Why to Adapt?

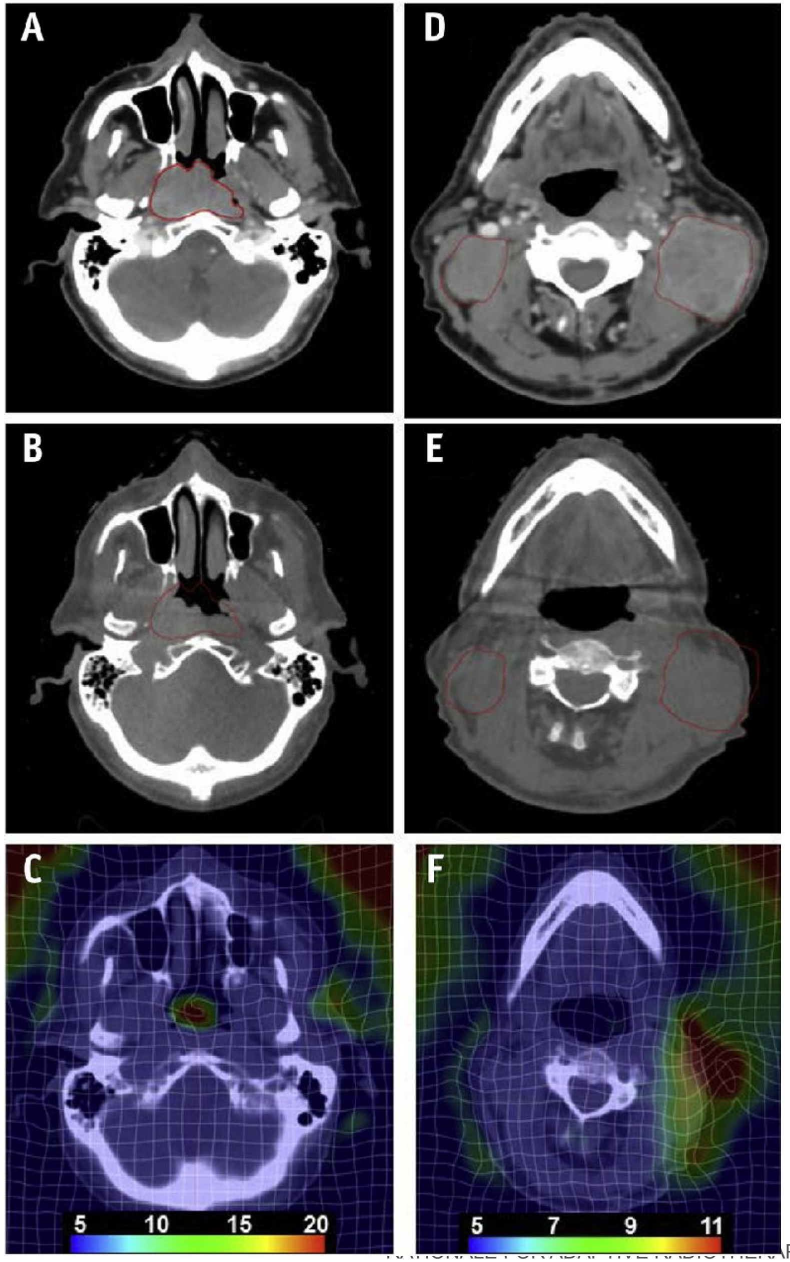
Anatomical Changes Requiring Adaptation:

- **Tumor Shrinkage**:
  - As the tumor responds to treatment, it can shrink significantly, especially in cancers like head and neck or lung cancer. ART ensures that the treatment field is adjusted to target the reduced tumor size effectively.
- **Organ Motion and Shifts**:
  - Internal organs can shift during treatment due to natural processes like bladder filling, bowel movement, or weight loss. ART helps correct for these changes by adapting the treatment plan.
- **Weight Loss**:
  - For patients with significant weight loss during treatment, especially in head and neck cancers, the shape and position of the tumor may change, requiring plan adaptation to avoid missing the target.

When and Why to Adapt?

Clinical Scenarios Where ART is Beneficial:

- **Head and Neck Cancer**:
  - Significant anatomical changes such as tumor shrinkage and patient weight loss can drastically affect treatment accuracy. ART ensures that the tumor remains fully targeted throughout the course of treatment.
- **Prostate Cancer**:
  - Organ motion, such as bladder filling or rectal gas, can cause shifts in the prostate’s position. Daily imaging and ART allow for adjustments to maintain precise targeting of the prostate.
- **Lung Cancer**:
  - Respiratory motion and tumor shrinkage over the treatment course require ART to maintain accuracy, especially for tumors located in mobile organs like the lungs.



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When and Why to Adapt?

Biological and functional changes:

- **Tumor Biology**: Changes in tumor perfusion or oxygenation may affect the tumor's sensitivity to radiation. ART can account for these biological changes, modifying the dose or plan accordingly to maximize treatment effectiveness.
- **Biology guided Radiotherapy**

ART is necessary in specific clinical scenarios where anatomical changes can compromise treatment accuracy, or biological changes compromise treatment efficacy.

TECHNOLOGICAL ADVANCEMENTS ENABLING ART

Technological Advancements Enabling ART

Imaging Technologies:

- **Cone Beam CT (CBCT)**:
  - **Function**: CBCT provides 3D imaging before each treatment session, allowing clinicians to see how the patient's anatomy has changed since the last session.
  - **Benefit**: This allows daily or frequent verification of tumor and organ positions, ensuring that the treatment plan is adjusted as necessary. CBCT is often used in head and neck, lung, and prostate cancer treatments.
- **MR-Guided Radiotherapy**:
  - **Function**: Real-time MRI imaging provides superior soft-tissue contrast, allowing for continuous monitoring of tumor and organ motion during treatment.
  - **Benefit**: MR-guided systems (ViewRay's MRIdian or Elekta Unity), enable real-time adaptation by tracking soft tissues throughout the treatment session, making ART more precise and dynamic.

Technological Advancements Enabling ART

Treatment Planning Systems (TPS):

- **Quick Re-Optimization**:
  - Modern TPS allows rapid re-optimization of the treatment plan based on updated imaging data. This means that after each CBCT or MRI session, the plan can be recalculated to reflect the current anatomy.
- **Real-Time Adaptation**:
  - Some advanced systems integrate imaging and treatment planning to allow real-time adjustments to the radiation beam, particularly in MR-guided systems.

Technological Advancements Enabling ART

Automated Re-Planning:

- **Function**: Automated tools allow for faster adaptation of the treatment plan without the need for manual intervention, reducing the burden on clinicians and speeding up the ART process.

- **Application**: As technology evolves, AI and machine learning will further enable automated, real-time adaptation, making ART more efficient and accessible.

ART is driven by innovation in imaging and treatment planning technology, which allows for precise, real-time adaptation of the treatment plan

CURRENT CLINICAL PRACTICES

Current Clinical Practices

Head and Neck Cancer:

- **Use of ART**: Head and neck cancers often require ART due to significant anatomical changes like tumor shrinkage and weight loss over the course of treatment.

- **Outcome Improvements**: Studies have shown that ART reduces side effects (e.g., xerostomia) and ensures better tumor control by maintaining accurate dose delivery to the tumor while sparing healthy tissues such as salivary glands.

Current Clinical Practices

Prostate Cancer:

- **Daily Adjustments for Organ Motion**: ART is frequently used in prostate cancer treatments to account for daily variations in bladder and rectal filling, which can shift the prostate's position.

- **Improved Targeting**: By adapting the treatment plan each day, ART ensures that the prostate receives the correct dose while minimizing radiation exposure to surrounding organs like the bladder and rectum.

Current Clinical Practices

Lung Cancer:

- **Managing Respiratory Motion**: Lung cancer patients benefit from ART as it accounts for respiratory motion and tumor shrinkage over the course of treatment. Adaptive techniques like respiratory gating and real-time imaging ensure that the tumor is accurately targeted despite breathing movements.

- **Outcome Enhancements**: ART helps reduce the risk of radiation pneumonitis by minimizing the dose to healthy lung tissue while maintaining precise targeting of the tumor.

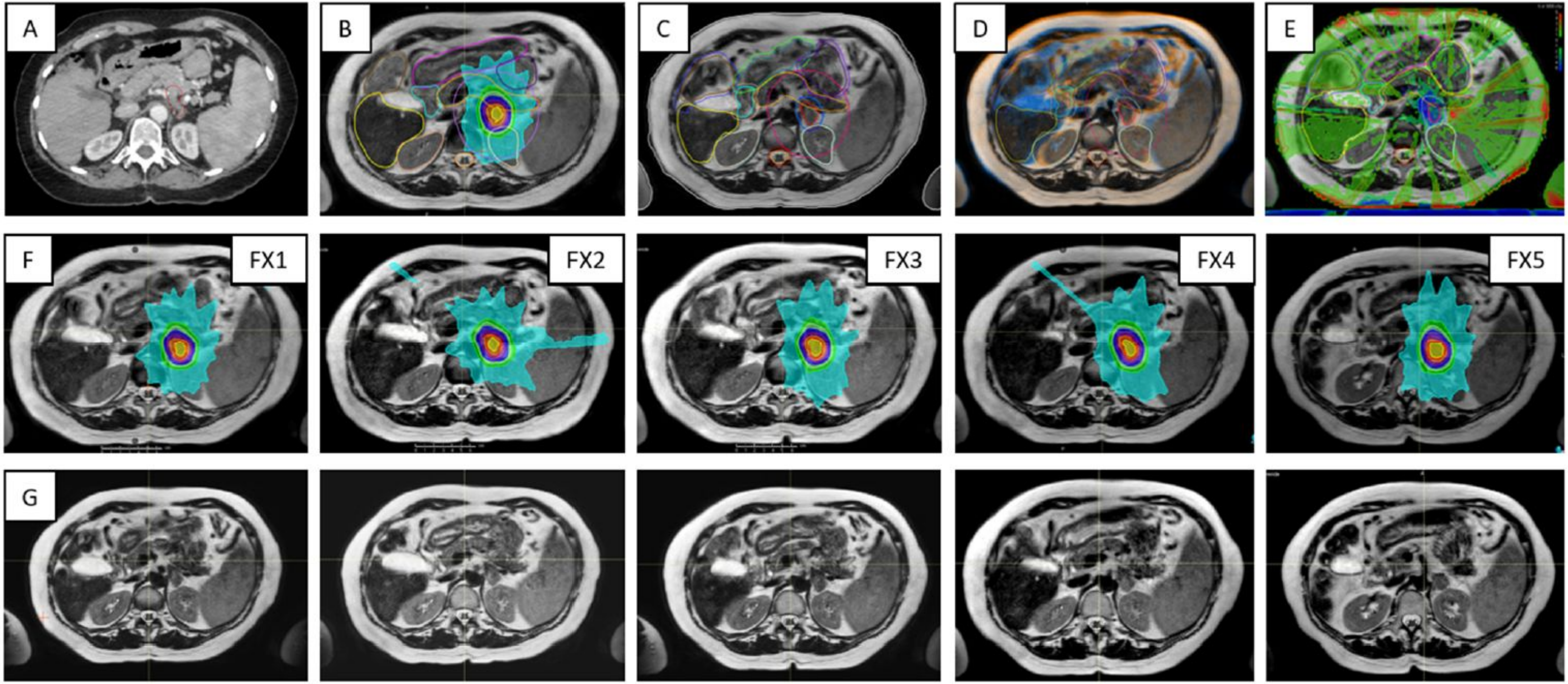
Current Clinical Practices

Pancreatic Cancer (with MRI-Guided Radiotherapy):

- **Use of MRI-Guided ART**: Pancreatic cancer is treated using MRI-guided radiotherapy (MRgRT) to manage tumor motion and adjust for nearby organ movement, such as the stomach or intestines.

- **Real-Time Adaptation**: With MRgRT, clinicians can continuously visualize the tumor and surrounding tissues in real time, allowing for adaptive adjustments during treatment. This is particularly useful for pancreatic tumors that move due to respiration or changes in gastrointestinal function.

- **Outcome Enhancements**: MRgRT improves the accuracy of dose delivery, reduces radiation exposure to the surrounding gastrointestinal organs, and helps manage treatment in cases where pancreatic tumors are in close proximity to critical structures.



Cancers **2022**, 14, 716. https://doi.org/10.3390/cancers14030716

Current Clinical Practices

ART has been validated in various clinical trials, showing improved outcomes, reduced toxicity, and higher overall survival rates in patients treated with adaptive techniques.

- Improved local control (H&N, Lung)
- Margins reduction (Lung, prostate,
- Improved target dosimetry (H&H, prostate, GYN)
- Reduce toxicity (Lung, prostate, GYN, Pancreas)
- Improve survival (Pancreas)

Current Clinical Practices

Head and Neck Cancer

1. **Schwartz et al., 2012** (Prospective, Offline/CT-on-rails)
   - 22 patients, one adaptive plan (ART1), 8 of 22 had two adaptive plans (ART2).
   - Trigger: Changes in CTV and OARs.
   - **Results**: ART reduced dose to parotid glands, improved target coverage.
   - **Outcome**: Significant dosimetric improvement with ART.
2. **Chen et al., 2014** (Retrospective, Offline/CT and MVCT)
   - 51 ART patients, 266 non-ART patients.
   - Trigger: Weight loss, mask fit, tumor shrinkage.
   - **Results**: Improved locoregional control, no difference in overall survival or toxicity.

Non-small Cell Lung Cancer

3. **Kong et al., 2017** (Prospective, Phase II, Offline/PET-CT)
   - 42 patients, adaptive boost after initial dose of 50 Gy.
   - Trigger: PET-CT resimulation after 40-50 Gy.
   - **Results**: 2-year local control of 82%, overall survival 52%, with reduced toxicity.
4. **Spoelstra et al., 2009** (Prospective, Offline/4DCT)
   - 24 patients, re-plan triggered by PTV reduction.
   - **Results**: Limited role for ART when using 4DCT to define margins, PTV reduction observed in most patients.

Current Clinical Practices

Prostate Cancer

5. **Deutschmann et al., 2012** (Prospective, Online/kV Imaging)
   - 39 patients, online aperture adaptation based on daily shifts.
   - **Results**: Allowed reduction in planning margins, ensuring safe treatment delivery with reduced toxicity.
6. **Keall et al., 2018** (Prospective, Online/MLC Tracking)
   - 28 patients, MLC tracking improved beam-target alignment and reduced dose variations.
   - **Results**: Improved dosimetry and alignment with real-time tracking.

Cervical Cancer

7. **Lim et al., 2014** (Prospective, Offline/MRI)
   - 30 patients, adaptive IMRT strategies.
   - **Results**: Improved target dosimetry and reduced OAR doses in most patients.
8. **Buschmann et al., 2018** (Prospective, Offline/CBCT)
   - 16 patients, plan-of-the-day technique based on daily bladder filling.
   - **Results**: Reduced bladder and rectum dose with adaptive planning.

Pancreatic Cancer

9. **Rudra et al., 2019** (Retrospective, Online/MR-based)
   - 44 patients treated with adaptive MR-guided radiotherapy.
   - **Results**: Improved survival and local control with dose-escalated adaptive treatment, no grade 3+ GI toxicity observed.

CHALLENGES AND LIMITATIONS

Challenges and Limitations

Time and Resource Demands:

- **Frequent Imaging**: ART requires daily or frequent imaging, such as CBCT or MR-guided imaging, to monitor anatomical changes. This can significantly **increase treatment time** compared to conventional static plans.
- **Re-Planning**: Adjusting the treatment plan based on new imaging data requires additional time for re-optimization and verification, which can place a burden on clinical staff and **extend treatment sessions**.

Technological Hurdles:

- **Availability of Advanced Imaging Systems**: **Not all treatment centers have access to the advanced imaging systems** (e.g., MR-guided radiotherapy, CBCT) necessary to implement ART effectively.
- **Infrastructure and Software**: ART requires sophisticated treatment planning software that can rapidly re-optimize the plan based on updated imaging data. The **cost and complexity of these systems can be prohibitive for some institutions.**

Challenges and Limitations

Staff Training and Expertise:

- **Specialized Knowledge**: Implementing ART requires a **team of well-trained clinicians, physicists, and dosimetrists** who are familiar with adaptive techniques and technologies.
- **Increased Workload**: Clinicians and physicists need to spend additional time reviewing daily imaging, re-optimizing plans, and ensuring quality assurance, which can increase their overall workload.

Cost Considerations:

- **Higher Costs of ART**: The need for more frequent imaging, advanced technology, and longer treatment times can result in higher costs compared to conventional radiotherapy.
- **Cost-Benefit Analysis**: For some patients, the additional cost and time investment of ART may not yield significant benefits compared to conventional radiotherapy.

CONCLUSION

Conclusion

Summary of ART's Importance:

- **Adapting to Anatomical Changes**: ART is a powerful solution for adapting to patient-specific anatomical changes that occur during the course of radiotherapy, ensuring the treatment remains accurate and effective.
- **Precision and Safety**: By continuously modifying the treatment plan, ART improves dose precision and minimizes radiation exposure to healthy tissues, enhancing both treatment efficacy and patient safety.

Takeaway Message:

- **ART Improves Outcomes**: ART is a vital tool in modern radiotherapy, addressing the limitations of static treatment plans. It ensures that the tumor receives the prescribed dose, even as the patient's anatomy changes, while reducing side effects.
- **Future Potential**: With continued technological advancements, ART will only become more effective and widely adopted, improving cancer treatment outcomes across various clinical settings.