AI Agents for Adaptive Radiotherapy

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Radiotherapy Now

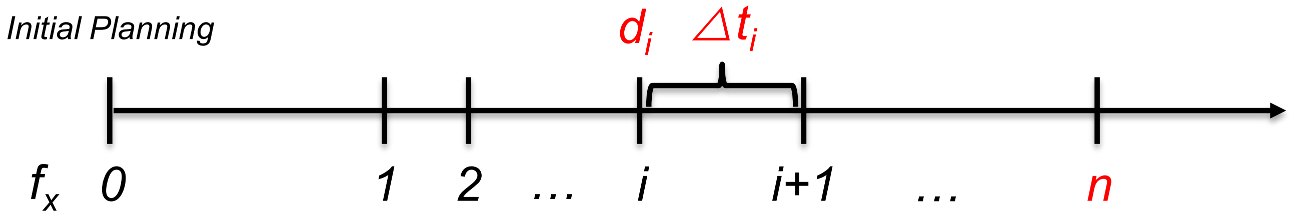
- For 100 years:
  - Treatment dose = 2 Gy
  - Time between dosing = 1 day
  - Total dose = 60-70 Gy
- More recently:
  - Treatment dose = 18 Gy
  - Time between dosing = 1-3 days
  - Total dose = 54 Gy

All potential variables. All fixed as constants

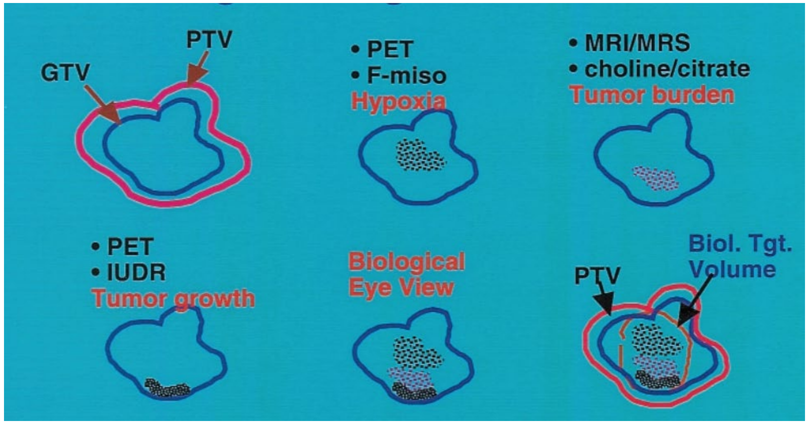
- All given in a *course* of radiotherapy
  - All patients get same treatment
  - Without interruption
  - Monitoring for acute toxicity
- Benefit and harm assessed relatively long AFTER completion of all Rx

Slide Courtesy of Dr. Robert Timmerman

From "One Size Fits All" to Personalization



- **Possible variables for personalizing RT**
  - Number of fractions (*n*)
  - Fractional dose (d_i)
  - Time interval between 2 fractions (Δt_i)
  - (Integration with systemic therapies)
- **"One size fits all" RT (for a particular patient cohort)**
  - n, d_i, Δt_i are all constants
- **Personalized RT**
  - *n* is a parameter to be optimized
    - Preliminary work at MGH: optimal stopping
  - d_i is a parameter to be optimized
  - $d_i = d_i(x)$ is also a function of space
    - Target delineation and dose painting
  - Δt_i is a parameter to be optimized



Clifton Ling et al, Int. JROBP, 2000

Two Dimensions in Personalized RT

- **Upfront patient stratification**
  - Biological factors
    - tumor genetics, molecular markers, etc
  - Tumor characteristics
    - Size, location, stage etc
  - Patient health status
    - age, comorbidities, and performance status, etc

- **Adaptive treatment during the course**
  - Anatomical imaging (MRI, CT) to assess anatomical changes (tumor size, shape, relationship with OAR, etc)
  - Biological markers to indicate how the tumor or normal tissues are responding
  - Functional imaging (MRI, PET) to assess changes metabolic activity etc

Two Types of Adaptive Radiotherapy

- **Gen 1: Anatomy-based**
  - **Goal**
    - Maximize tumor control and minimize toxicity based on anatomy change
    - $n, d_i, \Delta t_i$ are all constants
    - $d_i(x)$: target volume change based on anatomical imaging (MR, CT)
  - **Course correction and precise execution**
    - Deliver the original prescription precisely
  - **An advanced form of RT delivery**
    - There is where we are
    - Not true adaptation
    - The overall impact will be incremental
  - **Enabled applications**
    - margin-reduced (margin-less) RT
    - simulation-omitted RT (SORT)

Two Types of Adaptive Radiotherapy

- **Gen 2: Response-based**
  - **Goal**
    - **Maximize tumor control and minimize toxicity based on real-time response**
    - ***n***, d_i, Δt_i **are all variables**
    - $d_i(x)$: **intra-target volume change based on functional imaging (MR, PET)**
  - **Change prescription in response to tumor responses**
  - **A feedback mechanism in a control theory model**
  - **True adaptation and the future of RT**
  - **Response measured by (functional) imaging, biomarkers, etc**
  - **Response caused by perturbations**

IGRT → ART

- **Increased workload**
  - **Multiple planning sessions**
  - **Continuous team involvement**
    - **Ongoing collaboration among radiation oncologists, physicists, dosimetrists, and therapists throughout the treatment course**
  - **Time-intensive processes**
    - **Additional time is needed for repeated imaging, plan adaptations, and QA**

- **Increased complexity in workflow**
  - **Non-linear workflow**
    - **Complex, iterative process involving repeated cycles of imaging, planning, and treatment delivery**
  - **Integration challenges**
    - **Seamless real-time integration of imaging data into planning and delivery systems**
  - **Coordination of multiple disciplines**
    - **Synchronizing efforts across various specialists**

IGRT → ART

- **Increased complexity in technology**
  - **Advanced imaging systems**
    - High-quality and functional imaging modalities
  - **Sophisticated planning software**
    - Software capable of DRR, auto-segmentation, and real-time dose calculations
  - **Enhanced treatment equipment**
    - Linacs with integrated advanced imaging
  - **Greater data handling**
    - Significant data storage and computational power

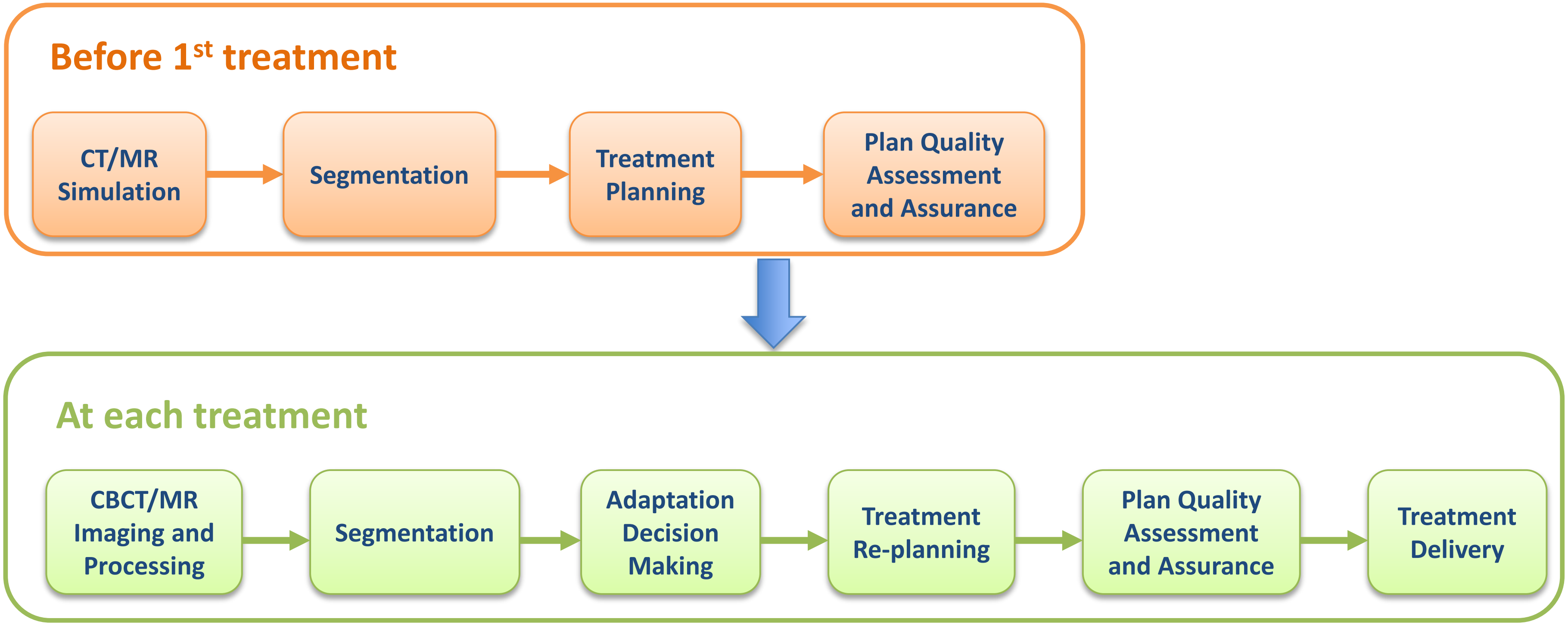
- **Increased challenges in decision-making**
  - **Ongoing clinical decisions**
    - Regular decision-making regarding treatment adaptations
  - **Personalized treatment adjustments**
    - Decisions tailored to individual patient responses
  - **Multidisciplinary input**
    - Input from various specialists, requiring effective communication and consensus-building

IGRT → ART

- Increased risk of errors
  - Frequent plan modifications
  - Coordination under time pressure
    - Multiple professionals to coordinate complex workflows using novel technologies under significant time pressure
  - Real-time decision-making
    - Less time for thorough verification
  - Complex procedures with advanced technologies

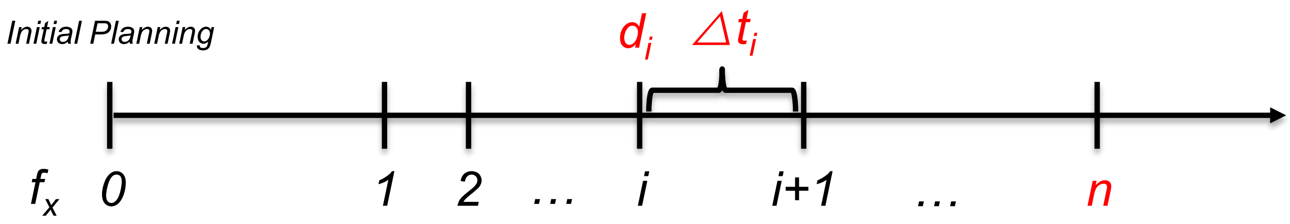
- Increased resource requirements
  - Skilled personnel demand
    - More time from highly trained staff for imaging, planning, and treatment delivery
  - Longer treatment sessions
  - Scheduling challenges
  - Continuous monitoring of treatment response

AI for Gen 1 ART (Anatomy-based)

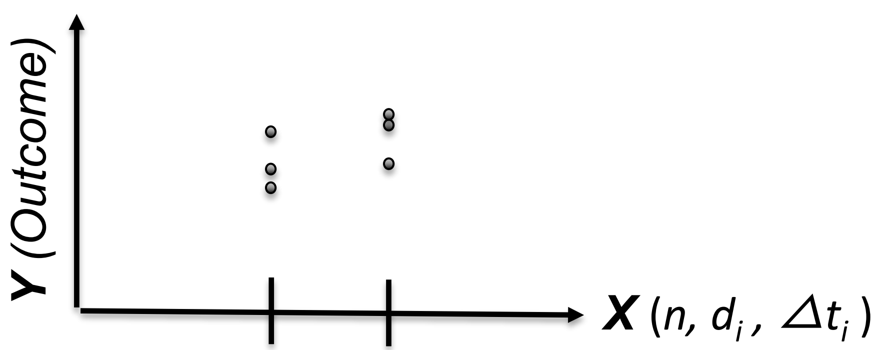


- Image acquisition
- Image processing
- Image segmentation
- Adaptation decision making
- Treatment re-planning
- Plan quality assessment
- Plan quality assurance
- Treatment delivery

AI for Gen 2 ART (Response-based)



- **AI is even more needed for Gen 2 than for Gen 1 ART**
- **AI-assisted decision making is essential since there are too many variables (*n*, d_i, and $\triangle t_i$)**
- **AI-powered automation workflow streamlining**
- **Main challenge**
  - **Lack of data covering a large spectrum of *n*, d_i, and $\triangle t_i$ to train AI models**
  - **Data from "one size fits all" RT is too narrow and uniform**

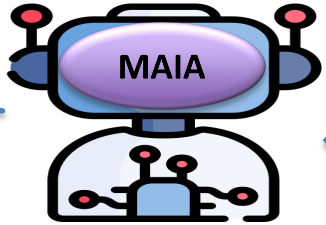


AI Assistant for Adaptive Radiotherapy

Retrieving, processing, analyzing, and presenting information — **Information**

Clinical decision support — **Decision**

Automating and streamlining clinical workflows — **Automation**



AI Assistant

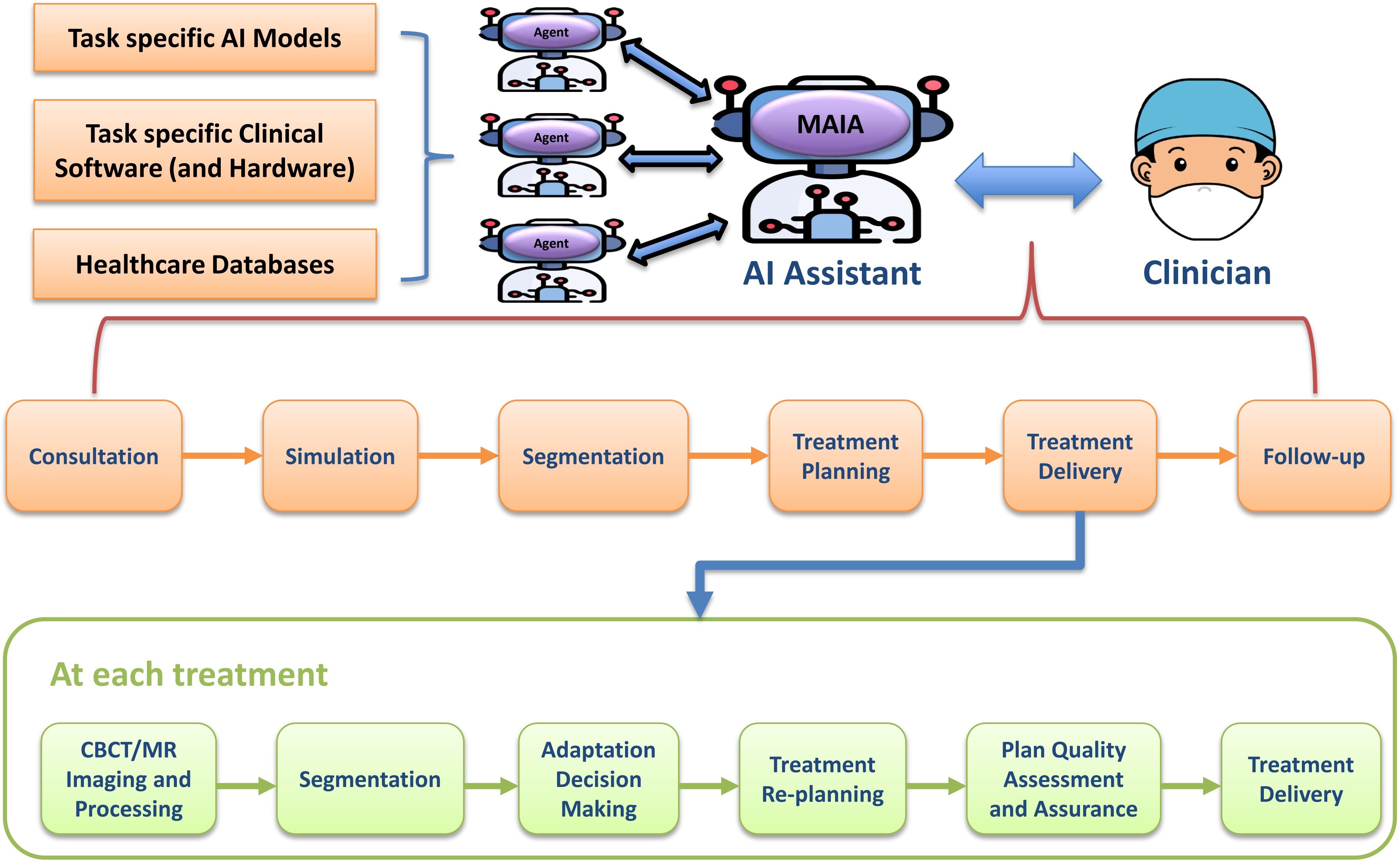
Clinician

Consultation → Simulation → Segmentation → Treatment Planning → Treatment Delivery → Follow-up

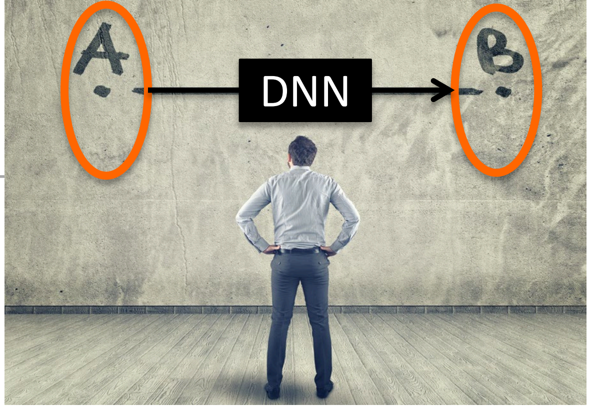
At each treatment

CBCT/MR Imaging and Processing → Segmentation → Adaptation Decision Making → Treatment Re-planning → Plan Quality Assessment and Assurance → Treatment Delivery

Multiple AI Agents for Adaptive Radiotherapy

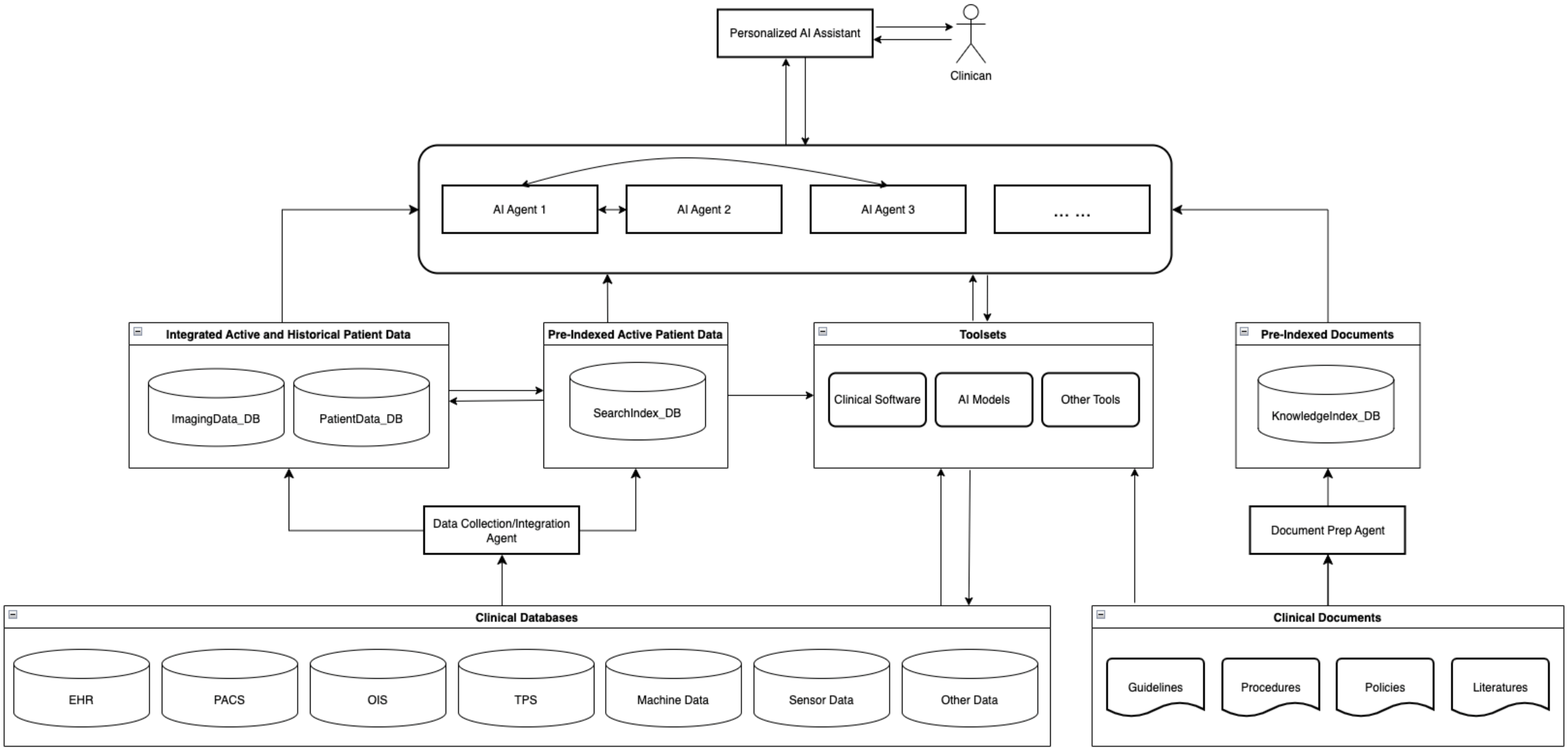


AI Agents vs AI Tools



- AI tools
  - e.g. supervised deep learning
  - Mapping from A to B
  - Fitting a complex mathematical function represented with DNN
  - A tool with zero intelligence
- AI agents
  - Can perceive, think, reason, make decisions, and take actions to achieve specific goals in an environment
  - Can also use tools to enhance their abilities, much like humans use software and devices
- Key capabilities of AI agents
  - Perception: gather and interpret data from the environment
  - Reasoning and decision-making: analyze information, predict outcomes, and select optimal actions
  - Autonomy: operate independently without continuous human input
  - Tool use: integrate and leverage external tools
  - Learning and adaptation: improve over time through experience and feedback

A Multi-Agent AI System for Adaptive RT



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Example AI Agents for Adaptive RT

- Data integration and summarization
  - Automated chart preparation
  - Clinical documentation assistance
- Task automation and workflow streamlining
  - Patient-trial matching
  - Simulation order automation
  - Auto-segmentation and treatment planning
- Treatment monitoring and quality assurance
  - AI-assisted plan review and QA
  - Real-time patient monitoring
  - AI watchdog for treatment safety
- Communication enhancement
  - Patient-facing chatbot
  - Clinician support chatbot
  - AI-powered chart round assistant
- Decision support
  - AI-driven treatment recommendations

A Clinically Viable AI Solution

- A single AI model is often not enough
- AI tools and AI agents need to work together
- A clinically viable solution requires a compound AI system is to ensure accuracy, safety, and adaptability
- A compound AI system integrates AI agents, AI tools, additional software tools, and databases

A Compound AI System for Segmentation

- More than just an auto-segmentation AI model
- Deployment and adaptation agent
  - Supports acceptance testing, model commissioning, and adaptation
  - Alignment with local clinical standards and patient population characteristics
- Segmentation workflow agent
  - Runs the auto-segmentation model
  - Reviews segmentation output and assesses quality
  - Suggests improvements and refines contours using additional AI models
  - Iterates the process until results meet clinical standards
- Performance monitoring and model maintenance agent
  - Continuously monitors model performance to detect data drift and performance degradation
  - Utilizes advanced tools for quality tracking and alerting users to necessary model updates
  - Facilitates periodic model retraining and updating

A Compound AI System for Decision Support

- **More than just a predictive AI model**
- **Clinical dashboard and visualization agent**
  - Retrieves and processes multi-source patient data
  - Presents key patient information in an intuitive format
  - Highlights tumor response trends, previous treatments, and risk factors
  - Enables interactive exploration of patient data
- **Predictive modeling and case-based reasoning agent**
  - Runs prognostic and predictive AI models for personalized treatment insights
  - Retrieves and compares similar cases previously treated
- **AI expert collaboration agent**
  - Simulates expert opinions from different specialties
  - Facilitates virtual tumor board by integrating insights from AI and human experts
  - Supports real-time peer collaboration and consensus-building
- **Clinical guidelines and literature agent**
  - Cross-references established guidelines
  - Summarizes newest clinical literature

Summary

- Response-based ART enables truly personalized radiotherapy with longitudinal adaptation
- AI-driven workflow automation, clinical decision support, and quality assurance ensure ART is scalable and clinically viable
- Single AI models are insufficient to handle the complexity of ART
- Compound AI systems, integrating AI agents, clinical software, and databases, provide a practical solution

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