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Applying High School Concepts in Medicine: Comparison of Metaheuristic Algorithms for Treatment Planning in Brachytherapy

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ABSTRACT

Introduction
Many of the mathematical principles used in medical physics such as geometric reasoning, exponential decay, iterative improvement, and basic probability, originate from concepts introduced in high school. This study illustrates how these foundational ideas can be applied to a clinically relevant problem by examining population-based optimization strategies for dwell-time planning in brachytherapy.

Methods
Two metaheuristic algorithms, Genetic Algorithms (GA) and Hippopotamus Optimization (HO), were implemented for optimization of the cylinder and tandem-and-ovoid brachytherapy. Dwell-time optimization is a simpler radiotherapy optimization problem, with the added advantage of calculating dose using concepts of exponential decay, also a part of high-school curriculum. GA, based on natural selection, is useful for students to understand the evolutionary process and the convergence to an optimal solution. HO, inspired by cooperative foraging dynamic, teaches about the balance between local and global exploration for a solution, while engaging in group behavior. During the search strategy target-coverage and organ-at-risk constraints were used so that the concepts of competing objectives and trade-offs can be learned. Multiple optimization runs were performed to evaluate convergence behavior, robustness, and computational efficiency.

Results
Both GA and HO produced clinically acceptable plans across both applicator types. For cylinder cases with only target-dose objectives, the algorithms achieved comparable coverage, converging within seconds. In the more complex tandem-and-ovoid geometry, GA converged more rapidly, though both methods achieved acceptable solutions without getting stuck in a local minima. The project advanced the understanding of core biological principles and optimization methodologies, while demonstrating their practical relevance to contemporary medical-physics challenges.

Conclusion
This work demonstrates that advanced treatment-planning optimization can be understood and implemented using ideas accessible at the high-school level. By framing metaheuristic optimization through familiar constructs such as probability, iterative improvement, genetics and teamwork we show that foundational mathematics and biology knowledge can be leveraged to address sophisticated clinical problems in brachytherapy

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INTRODUCTION

Medical Physics problems has overlap with lot of the concept learned in high school for their solutions.

One application of high school concepts is brachytherapy optimization which is one of the simplest optimization problems out there. Current brachytherapy optimization use simulated annealing or gradient descent methods. The question to explore is can concepts learned in high school such as genetics and group dynamics be applied to such a problem.

Two Meta-heuristic algorithms were considered for this purpose. Genetic Algorithm based on natural selection, is useful for students to understand the evolutionary process and the convergence to an optimal solution. Hippopotamus Optimization inspired by cooperative foraging dynamic, teaches about the balance between local and global exploration for a solution, while engaging in group behavior.

Application of these meta heuristic algorithms requires an understanding probability and statistics a concept that is learned in high school. Further since its application is for brachytherapy applications, chemistry concepts such as exponential decay, half-life etc. can be applied thus learning using valuable practical applications of things learned in the classroom

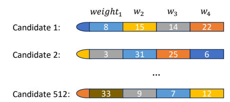
METHODS AND MATERIALS

META-HEURISTIC ALGORITHMS

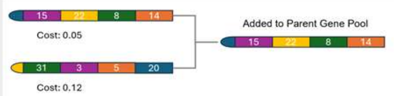
Meta-Heuristic Algorithms are a class of techniques used to solve complex problems when the exact solutions cannot be guaranteed. Genetic Algorithm (GA) is a population-based Meta-Heuristic optimization technique inspired by the principles of natural selection and genetics.

GENETIC ALGORITHM

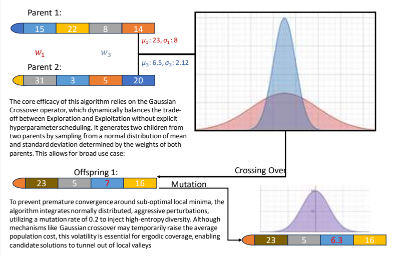
Initialization: The algorithm instantiates a population of 512 candidate solutions (NumCandidates). Each candidate represents a "chromosome", a vector of floating-point numbers (genes), where each number corresponds to a specific dwell time weight.



Cost Function: Fitness is inversely proportional to the cost function, defined as the Root Mean Square Error between the delivered dose and the target constraints. *Elitism* is used based on this computed cost to ensure the best solution is not degraded.



Tournament Selection: Two candidates are chosen at random; the one with the lower cost (better fitness) wins and becomes a parent. This applies evolutionary pressure (survival of the fittest). It increases the probability that good genetic material (effective dwell time combinations) is passed to the next generation while maintaining some diversity by not exclusively picking the absolute top candidates.



Early exploration: In early generations, parental vectors exhibit high Euclidean distance. This results in a flattened Gaussian curve, allowing the search to "jump" widely across the solution space, effectively surveying the landscape. (RED).

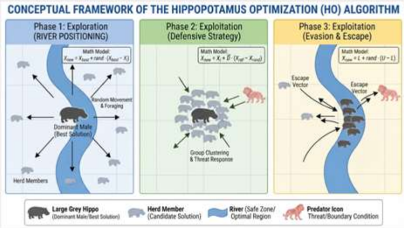
Late exploitation: As the population converges towards a minimum, the variance between parents diminishes. The Gaussian distribution narrows, restricting the search to the immediate neighborhood of the parents facilitating fine-tuning of the solution. (BLUE).

Genetic Algorithm Mechanism:
Elite solution is protected. However, the general population can temporarily worsen due to:
Aggressive Mutation: The mutation rate is set to a high to 20%. A beneficial weight configuration can be randomly perturbed into a detrimental one to "jump" out of local minima valleys in the non-convex space
Probabilistic Crossover: Offspring are generated via a probability distribution, possibly generating a child located further from the optimal valley than either parent, effectively increasing cost for that lineage.

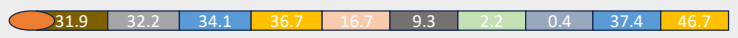
Hippopotamus Optimization

Hippopotamus Optimization (HO) is a nature-inspired optimization algorithm that simulates herd dynamic while perfectly balancing Exploration and Exploitation The algorithm is applicable for non-linear problems.

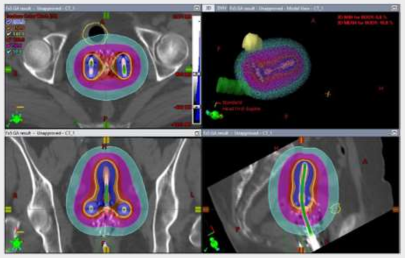
Social Structure: Hippos live in herds, led by a dominant hippo and its subordinates. Mimics movement around the safe zone and local exploration based on leader with best cost.
Habitat: Herd members dynamically alter their positions and executes exploitation to converge to local safe zones.
Defense: Hippos rely on group clustering and focus on isolation avoidance and localized threat deterrence



RESULTS



The top figure shows part of a resultant *Elite* Chromosome with genes showing the resultant times and the left figure shows the solution as input in the clinical software.



A clinical scenario with results from the GA optimization applied to a gynecological patient case.

DISCUSSION

Both meta-heuristic algorithms provided clinically viable solutions for cylinder and tandem and ovoid geometries. The convergence of the two techniques varied with GA having a faster convergence than HO for complex geometries.

GA is a good way for a high schooler to understand the concepts of evolution and genetics in a practical manner. Crossover, mutation and elitism are genetic concepts with a practical application for such a problem.

Social behavior and its applications and benefits can be understood via HO. Teamwork as well as group dynamics can be applied to an optimization problem and its convergence to an optimal solution can be observed

CONCLUSIONS

This work demonstrates that advanced treatment-planning optimization can be understood and implemented using ideas accessible at the high-school level. By framing metaheuristic optimization through familiar constructs such as probability, iterative improvement, genetics and teamwork we show that foundational mathematics and biology knowledge can be leveraged to address sophisticated clinical problems in brachytherapy.