Brachytherapy Dose Planning and Optimization Mini Project

Project Overview

This mini project implements a comprehensive brachytherapy treatment planning system using advanced numerical methods. The project demonstrates the application of optimization algorithms, interpolation techniques, and statistical analysis in medical physics.

Course Information

- **Course**: Numerical Methods
- **Topic**: Brachytherapy Dose Planning and Optimization
- **Implementation**: Python with Scientific Libraries
- **Algorithms**: TG-43 Dose Calculation, IPSA Optimization

Technical Implementation

1. TG-43 Dose Calculation Algorithm

The project implements the AAPM Task Group 43 (TG-43) formalism for brachytherapy dose calculations:

```
Dose Rate = S_k × Λ × G(r,θ) × g(r) × F(r,θ)
```

Where:

- S_k: Air kerma strength of the source
- Λ: Dose rate constant
- G(r,θ): Geometry function
- g(r): Radial dose function
- F(r,θ): Anisotropy function

Numerical Methods Used:

- Linear interpolation (SciPy interp1d) for TG-43 parameter lookup
- Trigonometric calculations for geometric relationships
- Vector operations for 3D spatial calculations

2. Optimization Framework

Implemented IPSA-style (Inverse Planning Simulated Annealing) optimization using:

Mathematical Formulation:

```
minimize: Σ(w_target × penalty_target + w_OAR × penalty_OAR + w_reg × penalty_regularizat
subject to: 0 ≤ dwell_times ≤ 100 seconds
```

Numerical Methods Used:

- L-BFGS-B constrained optimization algorithm
- Gradient-based minimization
- Penalty function methods

3. Clinical Case Simulation

Created a realistic prostate HDR brachytherapy case:

- 18 dwell positions in 2 catheters
- 11 target volume sampling points
- 10 organ-at-risk sampling points
- 600 cGy prescription dose

Results and Analysis

Optimization Performance

Metric	Initial Plan	Optimized Plan	Improvement
Target V100 Coverage	100.0%	100.0%	Maintained
OAR Mean Dose	1209.5 cGy	369.2 cGy	69.5% reduction
Hot Spots (V150)	100.0%	81.8%	18.2% reduction
Treatment Time	270.0 sec	81.8 sec	69.7% reduction

Clinical Quality Indicators

- **Target D90**: 734.3 cGy (adequate coverage)
- **OAR Sparing**: 100% of OAR points below 70% prescription dose
- **Plan Optimization**: Converged to global minimum (objective = 0.0)

Numerical Methods Demonstrated

1. Interpolation Techniques

- **Linear Interpolation**: Used for TG-43 parameter lookup tables
- **Boundary Handling**: Extrapolation for out-of-range values
- **Multi-dimensional Interpolation**: For anisotropy function

2. Optimization Algorithms

- **Constrained Optimization**: L-BFGS-B for bound constraints
- **Objective Function Design**: Multi-criteria penalty formulation
- **Convergence Analysis**: Gradient-based stopping criteria

3. Statistical Analysis

- **Dose-Volume Analysis**: Percentile calculations for clinical metrics
- **Performance Metrics**: Coverage indices and quality indicators
- **Comparative Analysis**: Before/after optimization comparison

Software Engineering Features

Code Organization

- **Object-Oriented Design**: Classes for dose calculators, plans, and optimizers
- **Data Structures**: Dataclasses for clean data representation
- **Type Hints**: Complete type annotation for code clarity
- **Documentation**: Comprehensive docstrings and comments

Error Handling

- **Singularity Avoidance**: Minimum distance constraints in dose calculations
- **Bounds Checking**: Safe interpolation with boundary handling
- **Input Validation**: Parameter range verification

Visualization and Output

- **Dose Distribution Grids**: 3D spatial dose mapping
- **Dose-Volume Histograms**: Statistical dose analysis
- **Optimization Tracking**: Convergence monitoring
- **Clinical Reports**: Automated metrics generation

Project Deliverables

Code Files

1. **brachytherapy_optimization_project.py** - Complete implementation
2. **dose_distribution_data.csv** - 3D dose grid (168 points)
3. **dose_volume_histogram.csv** - DVH analysis data (100 points)
4. **dwell_times_analysis.csv** - Optimization results (18 positions)
5. **project_summary_report.txt** - Detailed analysis report

Visualizations

1. **Dose Metrics Comparison Chart** - Bar chart showing optimization improvements
2. **Dose-Volume Histogram** - DVH curves for target and OAR volumes

Educational Value

Numerical Methods Concepts

- **Interpolation**: Practical application of scientific data lookup
- **Optimization**: Constrained minimization with real-world constraints
- **Linear Algebra**: Vector operations and geometric calculations
- **Statistics**: Percentile analysis and quality metrics

Medical Physics Applications

- **Radiation Therapy**: Clinical treatment planning workflow
- **Dose Calculation**: Physics-based modeling of radiation transport
- **Treatment Optimization**: Multi-objective clinical decision making
- **Quality Assurance**: Validation against clinical standards

Future Enhancements

Advanced Algorithms

1. **Monte Carlo Dose Calculation** - More accurate dose modeling
2. **Multi-Objective Optimization** - Pareto-optimal solution sets
3. **Evolutionary Algorithms** - Alternative optimization approaches
4. **Robust Optimization** - Uncertainty handling

Clinical Integration

1. **DICOM Integration** - Real patient data import
2. **Advanced Anatomy Models** - Heterogeneous tissue modeling
3. **Real-Time Planning** - Interactive optimization
4. **Machine Learning** - Automated parameter tuning

Conclusion

This mini project successfully demonstrates the application of numerical methods to solve a complex medical physics problem. The implementation showcases:

- **Technical Competency**: Advanced programming and algorithm implementation
- **Mathematical Understanding**: Proper application of optimization theory
- **Clinical Relevance**: Realistic medical problem with practical constraints
- **Engineering Practices**: Clean code, documentation, and testing

The achieved 69.5% reduction in organ-at-risk dose while maintaining 100% target coverage demonstrates the effectiveness of numerical optimization in improving patient care through better treatment planning.

References

1. AAPM Task Group 43: "Dosimetry of interstitial brachytherapy sources"
2. Computational Methods in Medical Physics
3. SciPy Optimization Documentation
4. Modern Brachytherapy Treatment Planning Systems

Project Statistics:

- **Lines of Code**: 400+ (with documentation)
- **Data Points Generated**: 450+ (dose distributions, DVH, analysis)
- **Optimization Variables**: 18 (dwell times)
- **Convergence**: 7 iterations to global optimum
- **Clinical Improvement**: 69.5% OAR dose reduction achieved