# From Concept to Clinic: How Our In-house Automated Planning System Augmented the Commercial TPS for Treating Over 10,000 Patients

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**Abstract** Most modern Treatment Planning Systems (TPS) come with Application Programming Interface (API) scripting capabilities, allowing for the development of custom applications that enhance the functionalities of commercial TPS. In our clinic, we have developed and integrated ECHO (Expedited Constrained Hierarchical Optimization), an in-house automated planning system, with the Eclipse TPS. ECHO has played a pivotal role in the treatment of over 10,000 patients. It streamlines the planning process: after preparing the contours and beams (IMRT fields or VMAT arcs), users launch the ECHO plug-in within the TPS, select optimization structures, and run the program. ECHO automatically retrieves necessary data from the TPS, constructs and solves optimization problems, and imports the final results (optimal fluence for IMRT, optimal control points for VMAT) back into the TPS. It then runs final dose calculation in TPS and notifies the user via email for plan review, all within 15-120 minutes. ECHO completely bypasses TPS optimization engine, however, it utilizes TPS's final dose calculation and, for IMRT, leaf sequencing. In this work, we discuss our development journey and clinical experiences, outlining both past and current technical challenges, along with the solutions we have devised. We have also recently introduced an open-source project, PortPy (Planning and Optimization for Radiation Therapy in Python), which aims to share our experience with the wider research community.

## 1 Introduction

Despite advancements, radiotherapy treatment planning remains a complex, time-consuming, and labor-intensive process, with the quality of plans often depending on the experience and skills of the planners. Automated planning has been a significant focus in the scientific community for approximately two decades, leading to many advancements[1–3]. However, the transition of research ideas into clinical practice by commercial vendors frequently takes years, and even when these innovations are introduced, clinics may not have access to the specific vendors or the products might not meet the unique needs of their criteria. For instance, a significant proportion of our patients (over 30% of our spinal patients) have undergone prior radiation, necessitating a customized plan that accounts for their previous treatments. Class-solution techniques, like the knowledge-based method found in the Eclipse system, is not applicable for these patients. Moreover, our clinical criteria undergo periodic revisions, potentially necessitating retraining for systems dependent on previous practices.

Most modern Treatment Planning Systems (TPSs) are equipped with API scripting capabilities, which allow researchers to enhance the functionalities of TPSs. Our group has developed a fully automated treatment planning system, named Expedited Constrained Hierarchical Optimization (ECHO), that integrates seamlessly with the FDA-approved Varian Eclipse system through API scripting and facilitated the treatment of over 10,000 patients to date. In this work, we will briefly explore some of the technical challenges we have faced, along with the solutions we have devised. To share our experience with the broader research community, our group has recently launched an open-source initiative, Planning and Optimization for Radiation Therapy in Python (PortPy). PortPy has seen over 7,000 downloads in the past four months, indicating its widespread adoption and use within the scientific community.

## 2 Materials and Methods

In the subsequent sections, we will briefly cover some of the hurdles encountered in creating a self-contained optimization engine designed to augment the commercial TPS. Table (1) provides a summary of these challenges, our technical solutions, their current implementation status within our clinic, and associated publications.

*Table 1. Challenges, Solutions, and Their Implementation Status in our Clinic.*

| Implement. Status | Challenge | Solution | Pub. |
|---|---|---|---|
| Deployed in clinic | Multi-criteria challenge | Hierarchical Opt. | 2,4 |
| R&D | | Deep Learning | 5 |
| Deployed in clinic | Dose discrepancy between opt. and final dose calc. | Lagrangian Method | 2,6 |
| R&D | | Compression | Ongoing |
| Deployed in clinic | Non-convex DVH constraints | Convex Approximation | 7 |
| Deployed in clinic | Non-convex VMAT | Sequential Convex Prog. | 6,8 |
| R&D | Reducing plan complexity | Wavelets | 9 |
| R&D | Proton beam selection | Bayesian optimization | 10 |
| R&D | Proton uncertainty management | Robust/distributed optimization | 11,12 |

**2.1 Non-convexity and Local Sub-optimality.** It is well-known that some treatment planning optimization problems lead to non-convexity, causing the optimization algorithm to potentially trap in a "local" sub-optimal solution and fails to reach the best "global" optimal solution. However, most of these non-convex problems can be solved to global optimality through the use of computationally demanding Mixed Integer Programming (MIP). While solving MIP problems might require days or weeks for a single patient, making it impractical for regular use, they can be solved in the absence of time constraint and serve as valuable benchmarks for validating more computationally efficient algorithms. Figure 1 showcases the comparison between the global optimal solution (solid lines) and the results of our algorithms (dashed lines) for two distinct non-convex optimization problems: 1) Intensity Modulated Radiation Therapy (IMRT) optimization with Dose-Volume Histogram (DVH) constraints[7] (left figure), and 2) Volumetric Modulated Arc Therapy (VMAT) optimization including direct machine parameter optimization[6,8] (right figure). These comparisons verify that our algorithms can generate solutions near the global optimal. Our open-source package, PortPy, enables researchers to achieve global optimal solutions for complex non-convex optimization problems, including those with DVH constraints, VMAT, and beam orientation optimization, further facilitating the development and validation of new techniques by the research community[13].

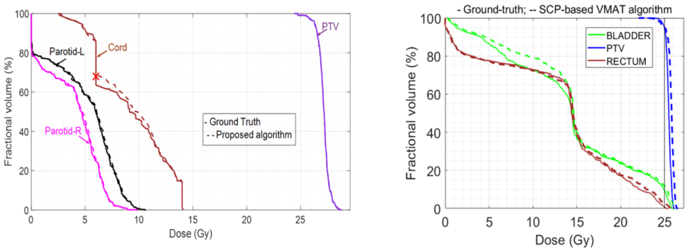


*Figure 1. The global optimal solutions (solid lines) for DVH constraints (left) and VMAT (right) are compared against the results of our algorithms (dashed lines).*

**2.2 Dose Discrepancy Between Optimization and Final Dose Calculation.** Treatment planning optimization necessitates the pre-calculation of the radiation dose delivered to the patient's body from thousands of small "beamlets", typically stored in a matrix known as the dose influence matrix or dose deposition matrix. This matrix represents the main computational challenge in optimization problems and is often truncated into a sparse matrix to enhance computational efficiency. However, this sparsification results in a discrepancy between the optimized dose and the finally calculated dose. While there are other sources of dose discrepancy, such as the tongue-and-groove effect and leaf transmission, their impact is usually much less significant. To mitigate this issue, a "correction loop" has been proposed in the literature[14], which periodically calculates a more accurate dose and reintegrates this information into the optimization problem for adjustments. This approach necessitates interruptions in the optimization algorithm, making it feasible only with simpler optimization algorithms like gradient descents, which are suitable for solving unconstrained optimization problems. Unfortunately, this technique is not applicable to more complex algorithms, such as interior point methods, which are utilized for solving constrained optimization problems. To overcome this limitation, we have proposed the reconstruction of an equivalent unconstrained version of a constrained problem using Lagrangian multipliers[2]. This approach allows for the correction of dose discrepancies without disrupting the optimization process. Although the "correction loop" strategy helps to reduce the dose discrepancy issue, it does not fully resolve it, and relying on such an *ad hoc* technique could potentially compromise the quality of the treatment plan. Upon a more detailed examination of the dose influence matrix, we have recently discovered that it is highly compressible, thanks to the correlations among machine parameters such as adjacent beams and beamlets. Our preliminary findings show an impressive compression rate of over 98% with a minimal error margin (approximately 2%). These results will be discussed in detail in a separate study. It is worth mentioning that our open-source initiative, PortPy, encompasses all necessary data for optimization, including the dose influence matrix, which has been pre-calculated for many patients (currently 50 lung patients) and extracted from the Eclipse system.

**2.3 Optimally Balancing Plan Complexity and Dose Conformity.** IMRT/VMAT effectiveness relies on conforming radiation dose to the tumor by modulating radiotherapy machine parameters (e.g., fluence, multi-leaf collimator). Although some modulation is necessary, increased modulation does not always enhance dose conformity, and excessive modulation can increase plan complexity and hinder the delivery accuracy. The importance of optimally balancing dose conformity and plan complexity has been long recognized, yet it remains a challenge as also noted in a 2020 Red Journal Editorial Note[15] and highlighted by ESTRO[16,17]. In IMRT, we have recently introduced a novel wavelet-based planning framework[9], which treats each beam's 2-dimensional modulated fluence as an image and utilizes advanced wavelet tools from imaging science to induce local and global fluence smoothness. This framework also allows for the proactive elimination of overly complex and clinically irrelevant plans by employing only low-frequency wavelets. For VMAT, we have recently developed a new VMAT planning framework, named Sequential Convex Programming[6,8] (SCP). The SCP-based VMAT framework is the first, to our knowledge, that fully integrates plan complexity into treatment planning and identifies a VMAT plan close to the “global” optimal plan.

**2.4 Safety of In-house Developed Software.** Integrating with a commercial TPS and conducting the final dose calculation and evaluation within it offers a level of reassurance. However, implementing a strict quality assurance (QA) protocol for in-house software development is crucial, particularly for applications like ours that entirely bypass the TPS optimization engine. Our team adheres to the guidelines outlined by Moran et al. (2022)[18] for the final evaluation and documentation of our in-house software projects. Moreover, we conduct thorough retrospective studies with randomly chosen patients, comparing the manually generated treatment plans used for treatment with those generated by our ECHO system, before introducing new disease sites or fractionation regimens (see Figure 4). Film and portal dosimetry, in alignment with departmental policies, are also utilized for QA purposes.

## 3 Results

Figure 2 illustrates the ECHO's system design and workflow. Once the structure contours and beams/arcs are set up, users launch ECHO as a plugin from the Eclipse TPS, selecting structures for optimization. The API then retrieves necessary patient data (e.g., beam parameters, influence matrix) for optimization. The system solves the optimization problems, importing optimal machine settings (fluence for IMRT, control points for VMAT) back into Eclipse for the final dose calculation. There is a correction-loop to align optimized and calculated doses. Lastly, an automated email notifies the user when the plan is ready for review. This workflow is fully automated, requiring user input only for initial contour and beam setup.

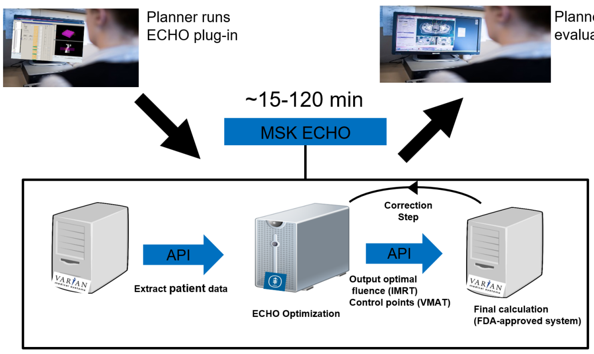


*Figure 2. ECHO workflow is fully automated using API scripting. ECHO completely bypasses the TPS optimization engine, but it relies on the TPS for final dose calculation and, in case of IMRT, for the final leaf sequencing as well.*

ECHO has played a pivotal role in the treatment of over 10,000 patients across a range of disease sites such as spine, prostate, lung, and oligometastases at our center. Figure 3 displays the monthly plan generation statistics through ECHO and the distribution across different disease sites.

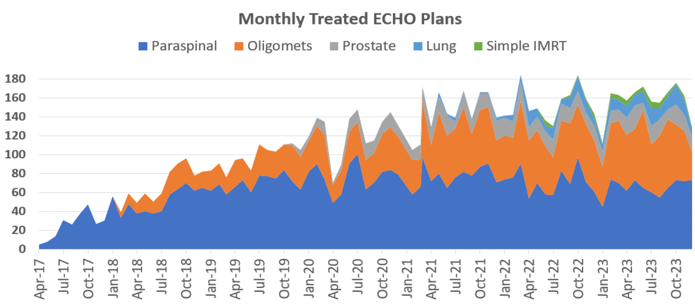


*Figure 3. About 180 plans are generated monthly using ECHO.*

As previously mentioned, we conduct a retrospective analysis of ECHO's performance prior to introducing a new site or prescription regimen. This analysis encompasses both quantitative comparisons using clinically relevant dose metrics, akin to those depicted in Figure 4, and qualitative evaluations of 3D dose distribution and DVH by experienced physicists and radiation oncologists.

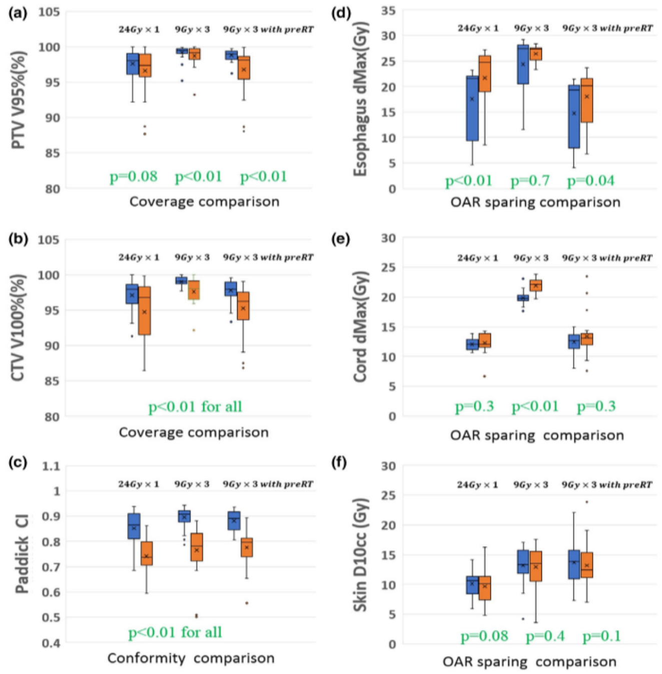


*Figure 4. Pre-clinical validation, conducted prior to clinical deployment of new site or prescription, includes simulating ECHO plans for previously treated patients and performing a comparative analysis.*

## 4 Discussion

API scripting, now accessible in major Treatment Planning Systems (TPS), serves as a robust mechanism to enhance clinical workflows through increased automation. This work demonstrates the integration of home-grown optimization techniques into clinical operations by extracting data from the TPS, executing optimization processes externally, and seamlessly reintegrating the results back into the TPS without manual intervention. However, it is important to acknowledge that API scripting, while transformative, is still an evolving technology and might not encompass all necessary functionalities. For instance, due to the limited API capabilities in the clinical version of Eclipse, we had to transfer patient data to a non-clinical version of Eclipse for processing. This process, though automated via Varian's DB Daemon transfer tools, introduces additional complexity.

The criticality of safety and quality assurance in the development of in-house software for critical applications like radiotherapy cannot be overstated. In addition to performing comprehensive and objective retrospective evaluations to determine the impact of the software on the quality of care, it is recommended to follow established guidelines, like those suggested by Moran et al.[18], to ensure the highest levels of safety and efficacy.

Finally, we hope our open-source project, PortPy, accelerates research in treatment planning optimization and encourages the development of new treatment planning techniques. These could potentially be applied clinically using API scripting, bridging the gap between research and clinical use.

## 5 Conclusion

We have developed and successfully implemented ECHO, a fully automated treatment planning system. Thanks to the integration capabilities provided by Eclipse API scripting, ECHO is now fully integrated with commercial TPS and seamlessly incorporated into our clinical workflow. ECHO has been instrumental in the treatment of over 10,000 patients, reducing the average planning time by half—from a full day to just half a day—while significantly improving the quality and consistency of treatment plans.

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