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INTRODUCTION

Recently, research efforts have begun to examine the combination of BNCT with external beam photon radiotherapy (Barth et al. 2004). In order to properly prepare treatment plans for patients being treated with combinations of radiation modalities, appropriate planning tools must be available. To facilitate this, researchers at the Idaho National Engineering and Environmental Laboratory and Montana State University have undertaken development of a fully multi-modal radiation treatment planning system.

METHODS AND MATERIALS

MINERVA is a patient-centric, multi-modal, radiation treatment planning system (RTPS) which can be used for planning and analyzing several radiotherapy modalities, either singly or combined, using common modality independent image and geometry construction and dose reporting and guiding. This system builds upon the experience accumulated from development of earlier systems for BNCT (Nigg et al. 1997, Nigg et al. 1999, Wessol et al. 2002). MINERVA is being developed with the Java (Gosling 1996) Virtual Machine for interoperability. MINERVA employs an integrated, lightweight plugin architecture to accommodate multi-modal treatment planning using standard interface components. The MINERVA design also facilitates the future integration of improved planning technologies.

The MINERVA design includes the three common software modules - image processing, model definition, and data analysis- used by any RTPS, along with a central patient module to coordinate communication and data transfer, as shown in the upper half of Figure 1. The source and transport plugin modules, shown on the left and bottom of Figure 1, communicate with these modules either directly through the patient database or through MINERVA's openly published, extensible markup language (XML)-based application programmer's interface (API). All internal data is managed by the database management system (DBMS) and can be exported to other applications or new installations through the API data formats.

RESULTS

The capabilities of the various modules that have been developed for the MINERVA system, shown as the solid outlined boxes in Figure 1, are described in this section.

Patient Module

The Patient module is the focal point of MINERVA. It manages the entire treatment planning process, launches and manages the Image, Model, and Analyze modules, and creates, edits, and retrieves data from the patient database. The Patient module is able to open a robust connection to the patient database using an Open Database Connectivity (ODBC) compliant database engine. The Patient module user interface allows the user to record, review, and edit patient information. A screen shot of the patient user interface is shown in Figure 2. This information includes general information about the patient (name, contact information, etc.), as well as physician data and treatment history. The patient module allows the user to see what data files are associated with a given patient. These files also can be dissociated from the patient.

Database and Data Management

MINERVA's data management system employs an interface layer to provide a framework for modules to communicate with the data sources. As a result, the data sources are loosely coupled to the rest of the system. This allows new data storage technologies to be added without cascading effects throughout the system. Although not all of the modules access all of the data sources, the data interface layer gives them the ability to do so if needed.

All patient data is stored in a relational database, removing the burden of tracking multiple patient files from the user. The Java Database Connectivity (JDBC) technology allows MINERVA to communicate with any database that has a JDBC driver available for it. Steps have been taken to ensure that the database integrity is maintained by storing a patient's information in several smaller tables and by supporting transactional tables.

A complete Extensible Markup Language (XML) file specification of all of the information contained in the database and a set of XML-based import/export tools have been developed. This same XML file specification will also be used to help define the API between MINERVA and the modality-specific transport modules. The XML-based tools allow any module that has access to the data interface layer to: import external patient XML files directly into the database; import XML files generated by an external plugin; export specific data needed by an external plugin to perform an operation; or export all or part of a patient's data.

Image Module

The Image module prepares and processes the images for use by the model module. The user interface for the Image module is shown in Figure 3. Full database connectivity was added to the Image module. The Image module currently supports DICOM-RT, QSH, JPEG, and raw image importation. The Image module, with the appropriate plugin, can convert externally formatted images to the internal MINERVA image format and store them in the patient database. Plugin support was also added so that image manipulation operations and image import filters can be added later by placing a plugin in the plugins folder. Standard image processing features, including noise filtering, gamma correction, and contrast enhancement, are also provided.

A rigid registration system based on maximization of mutual information (Viola and Wells 1997) has been included. To facilitate the registration, and define the univel geometry, a reslicing tool has been developed. This tool performs a pixel-by-pixel interpolation between existing image slices to define new images and create a uniform spacing between image slices.

Model Module

The Model module creates the anatomical geometry of the patient and target based on the image data received from the Image module. The Model module can be used to either create a new univel (Frandsen 1998) geometry file or edit an existing model. Anatomical structures are defined by various methods, and materials are assigned to these regions. The univel geometry permits very fast Monte Carlo analysis. The user interface and some of the features of the model module are shown in Figure 4.

The Model module contains several methods for manually or semi-automatically defining up to 65,536 regions of interest (ROIs) from multi-modal image sets. A variety of tools and operations are available to make manual ROI definition easy and fast as an interim solution until a suitable and robust automated procedure can be developed. All of these tools and operations have been implemented as plugins to simplify the program design and to allow the later addition of more advanced tools. A generic undo manager was added that allows the program to record the user's actions and later undo those accumulated actions if required. A single image view was added, so that the user can see and operate on one image slice at a time. All modeling can be conducted with multiple image sets along the three principal orthogonal axes simultaneously and interchangeably. Multiple image sets may be used simultaneously to define the ROIs. A 3D visualization view has been added which displays the current patient geometry and will update to give instant feedback.

Scripting support has been added by recording significant user actions to a file, which can later be played back. An entire modeling session can be recorded, or just a small portion to automate common tasks. By this feature, modeling sessions can be easily replicated or stored as planning templates. This has the capability to greatly simplify the modeling process.

Analyze Module

Control of the planning and dose reporting functions is consolidated in the Analyze module. The planning function controls the launching of the source and transport plugins, receives the results from these plugin modules, and saves the results to the database. The dose reporting function accesses the database to read the dose information for each field in the plan, and performs the dose combination and reporting.

The Analyze module can create multiple fields (irradiation configurations), plans (combinations of fields), and strategies (combinations of plans), and can combine multiple fields into plans, and multiple plans into strategies. Before inserting a field or a plan, basic checks are made to make sure they can be safely inserted, such as checking the various image dimensions and treatment modality types to assure consistency. The Analyze module launches source plugins to define the radiation sources, and transport plugins to calculate the dose data, needed to fully define each field. The interface to the transport plugins will export a field, with its associated source and geometry, to an XML file and import a dose data object from an XML file and associate it with the field.

The Analyze module merges the dose data from multiple fields into one dose data set for a plan, and merges multiple plans into a strategy. This merger can be customized by allowing the user to set modality-dependent biological weighting factors (RBE) by field, region, and dose component. Binary agents may also be included, with accumulation factors that may vary by region and compound type.

Analyze uses a plugin system to display the dose data to the user. This allows the users to customize the program by adding additional display plugins. Plugins to calculate and display contours, dose volume histograms, and dose depth data have been created. These plotting module plugins also use computational plugins so users will be able to write their own data analysis algorithms.

The contour plugin displays the dose data as contours drawn on top of an image set on all three principal axes, as shown in Figure 5. These contours will automatically update in the background as the user changes the weighting values for nearly instantaneous feedback.

The dose volume histogram (DVH) plugin will display the dose information based on the chosen graph type, as shown in Figure 6. It currently supports several different plot types, including plugins for cumulative, frequency, and volume graphs. The dose depth plugin will display dose information on a chosen line segment through a 3D region. Both plugins have automatic update as the user changes weighting values. The user is able to print, export, or save plots to the database for future use.

Neutron Transport Plugin

The neutron transport module is the computation engine for the external beam neutron therapy modalities (BNCT, fast neutron therapy, etc.) and also for internal localized and distributed neutron sources. This module computes flux and dose distributions from the patient geometry and radiation source distribution. A coupled neutron-photon calculation is performed, using the INEEL's patented univel geometry (Frandsen 1998). Continuous energy neutron and photon cross section data are used for the calculation, and are derived from the latest Evaluated Nuclear Data File (ENDF) data into an XML-based data format. A detailed photon production model is used. The photon transport calculation assumes charged particle equilibrium, so that explicit tracking of electrons produced by photon interactions can be neglected.

DISCUSSION

The lightweight common RTPS modules (Patient, Image, Model, and Analyze) are functionally complete. A full computation path has been established for MTR treatment planning, with the associated transport plugin developed by researchers at the Lawrence Livermore National Laboratory. Development of the neutron transport plugin module is proceeding rapidly, with completion expected later this year.

Future development efforts will include development of deformable registration methods, improved segmentation methods for patient model definition, and three-dimensional visualization of the patient images, geometry, and dose data. Transport and source plugins will be created for additional treatment modalities, including brachytherapy, external beam proton radiotherapy, and the EGSnrc/BEAMnrc codes (Kawrakow 2002, Rogers 2002) for external beam photon and electron radiotherapy. The interfaces for the common RTPS modules will be refined, in response to feedback from clinical test facilities.

ACKNOWLEDGEMENTS

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Viola P and Wells WM, 1997. Alignment by maximization of mutual information. Int J Comp Vis **24**(2) 137-154.

Wessol DE, et al., 2002. SERA – simulation environment for radiotherapy applications, user's manual version 1C0. INEEL-EXT-00698, Idaho National Engineering and Environmental Laboratory.

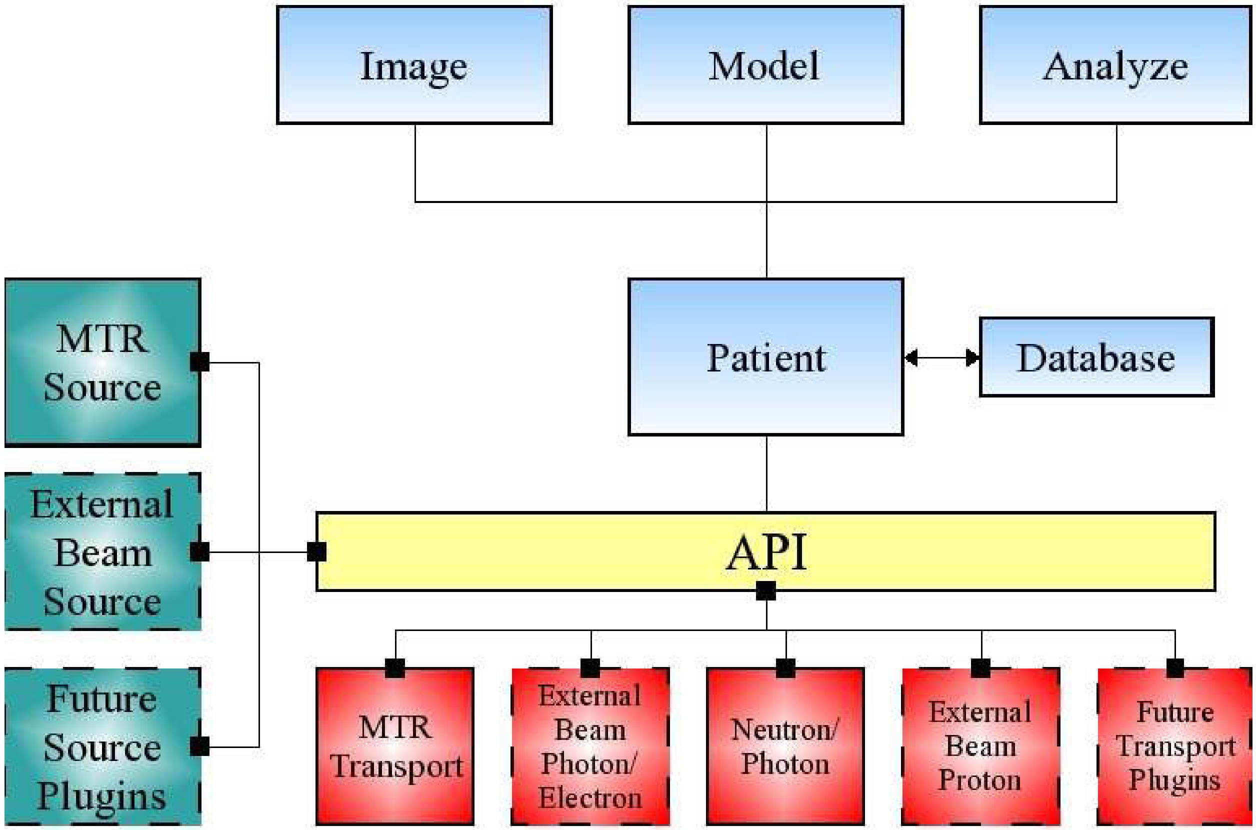

Figure 1. Basic design of the MINERVA treatment planning system. Dashed boxes represent future (to be developed) plugin modules.

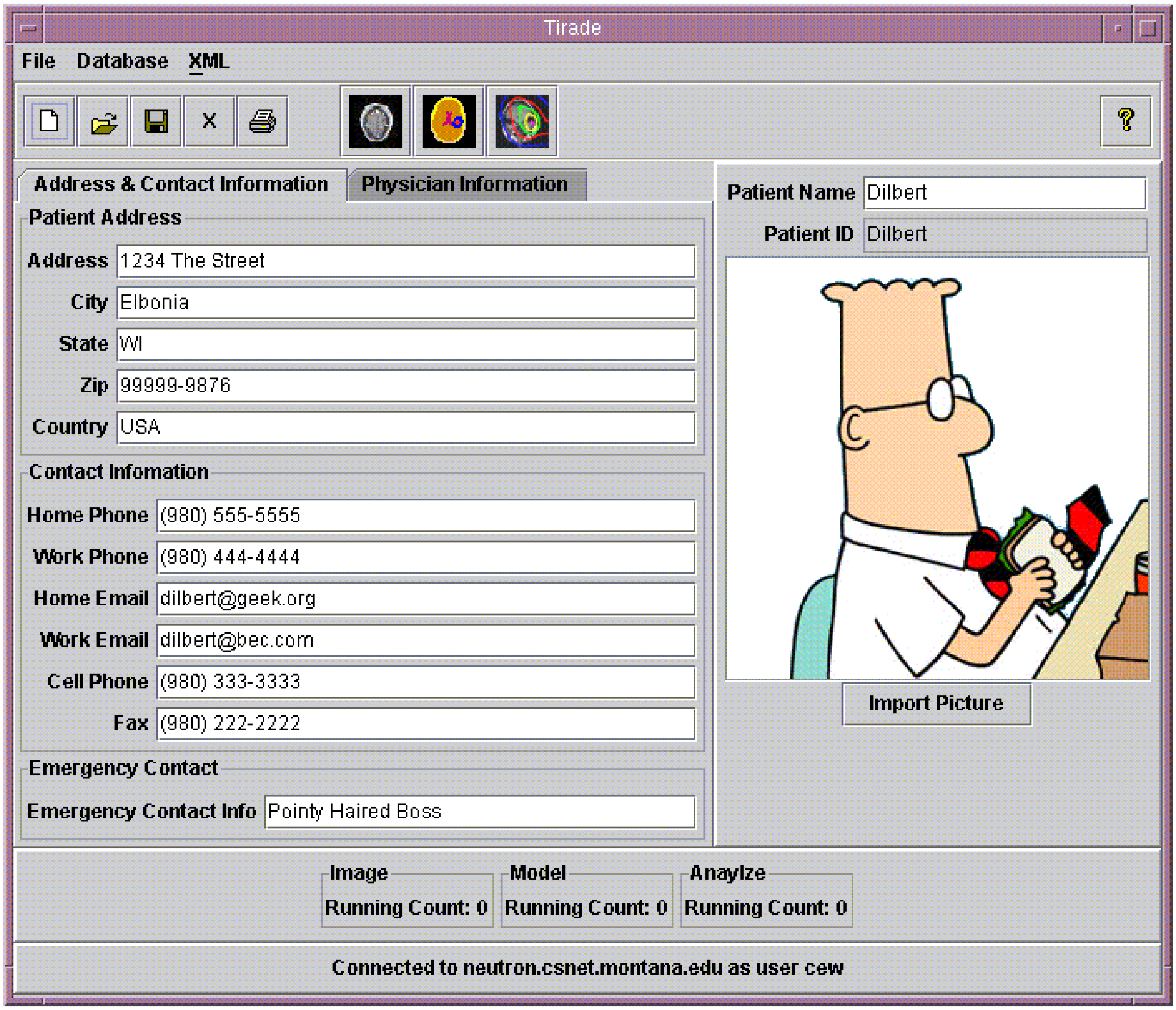

Figure 2. Screen shot of the Patient module user interface.

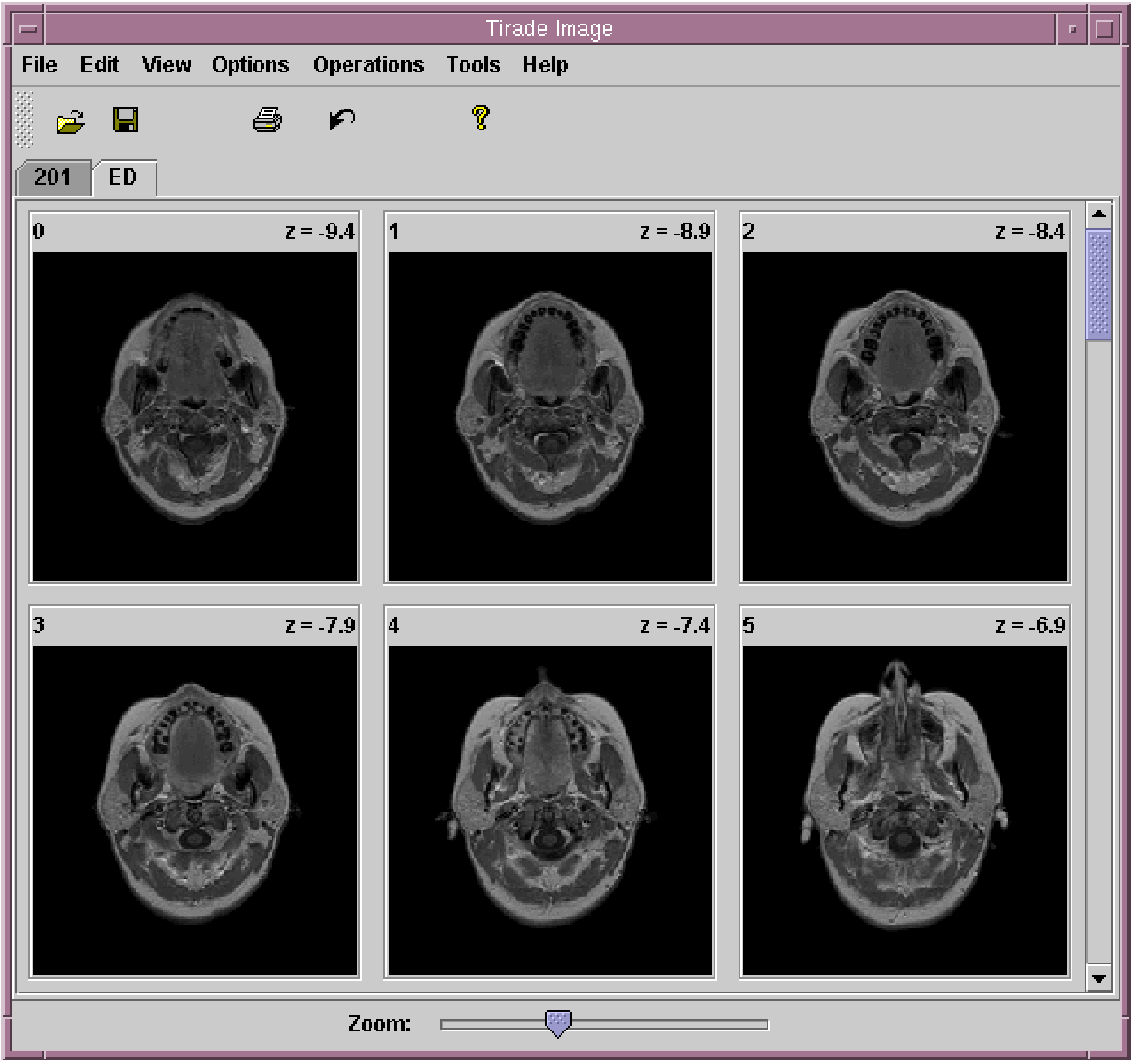

Figure 3. Screen shot of the Image module user interface.

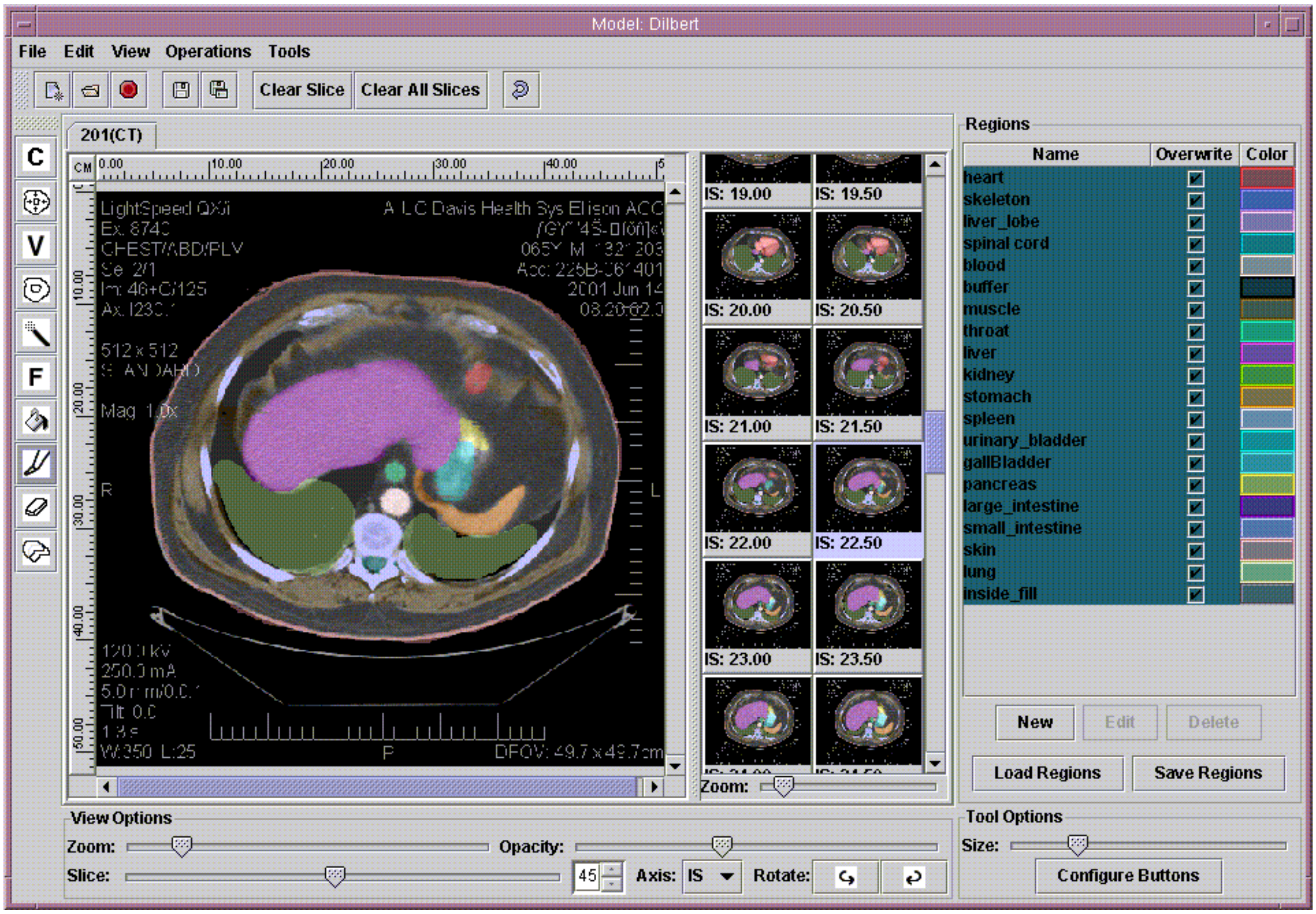

Figure 4. Screen shot of the Model module user interface.

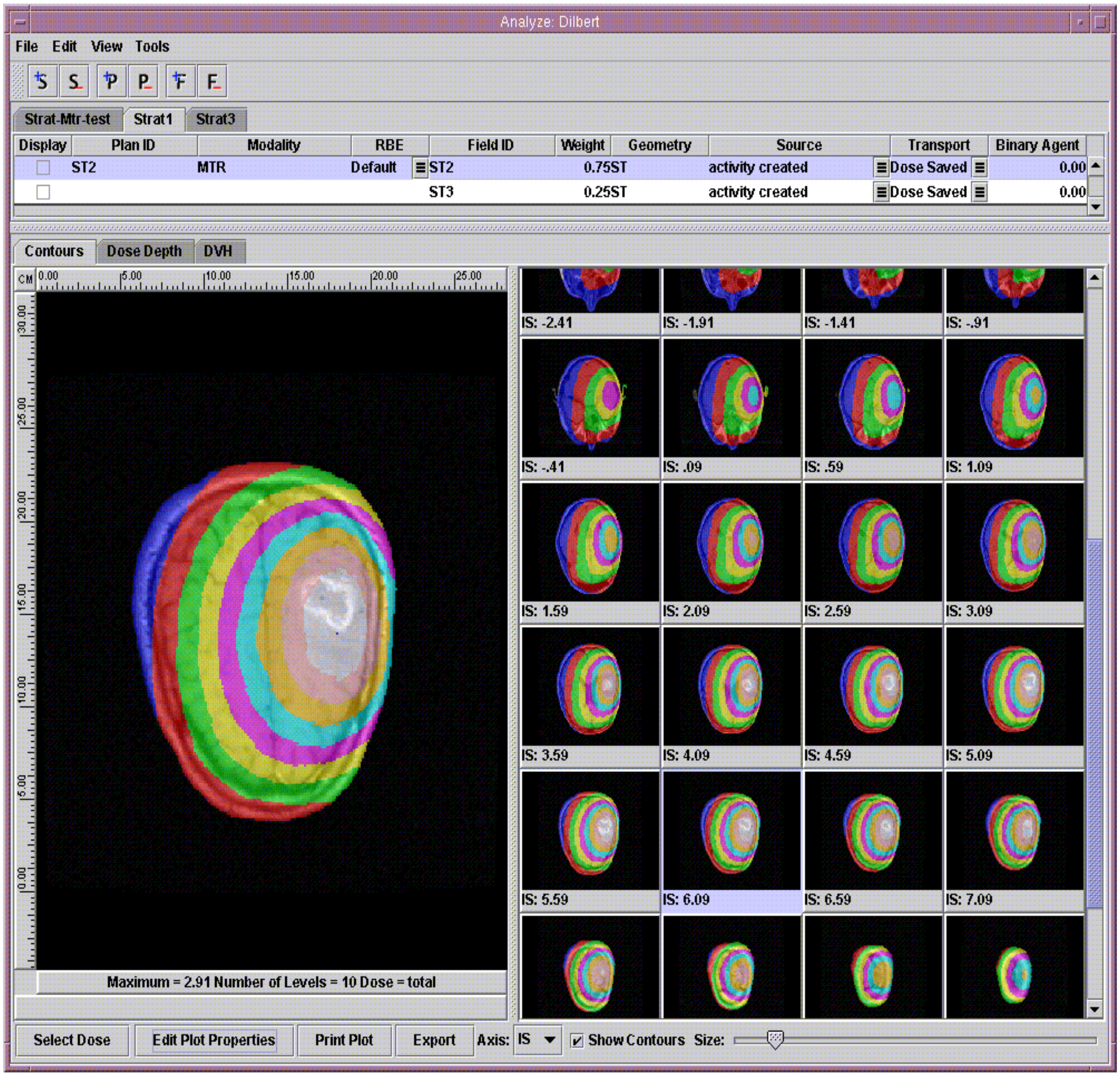

Figure 5. Screen shot of the Analyze module user interface.

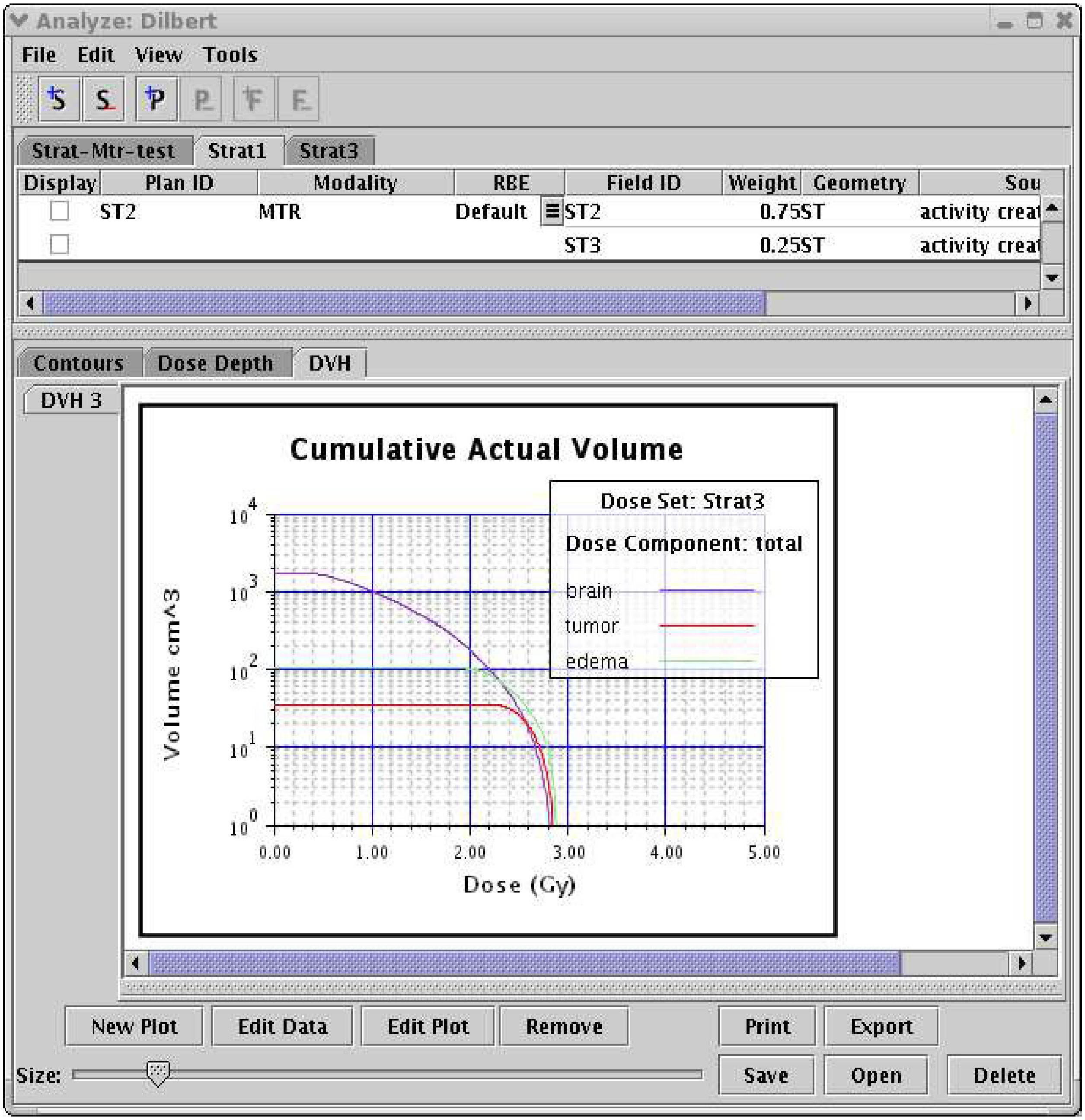

Figure 6. Screen shot of the Analyze module DVH display.