Radiation Treatment Planning Using Discrete Ordinates Codes

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INTRODUCTION

As oncologists are able to treat smaller tumors with more complex external beams, the ability to optimize radiation treatment planning (RTP) becomes very important. Historically, Monte Carlo codes have been used for this type of work since they are equipped to accurately treat charged particles. However, these codes take a long time to run to obtain statistically accurate results. Discrete ordinates codes run much faster than Monte Carlo codes but little experience exists in using these codes for charged particle transport. If discrete ordinates codes would be able to accurately model the electron transport in addition to the photon transport then these codes could be used to efficiently optimize beam treatment and a distinct advantage would be gained over Monte Carlo codes. As an example, the finite element, multi-group discrete ordinates code, ATILLA, has been successfully applied to 3D radiotherapy problems[1]. The DOORS-3.2 package developed by Oak Ridge National Laboratory was used for this work[2].

Problem Description

Charged particles pose a unique transport problem due to their scattering cross sections. The Boltzmann-Fokker-Planck (BFP) equation is able to handle charged particle scattering (see equation 1).

$$\begin{aligned}
&-\frac{\partial}{\partial E}[\beta(\vec{r},E)\psi] \\
&-T(\vec{r},E)\left\{\frac{\partial}{\partial\mu}\left[(1-\mu^2)\frac{\partial\psi}{\partial\mu}\right]+\frac{1}{1-\mu^2}\frac{\partial^2\psi}{\partial\varphi^2}\right\} \\
&+(\vec{\Omega}\vec{\nabla})\psi+\sigma_t(\vec{r},E)\psi(\vec{r},\mu,\varphi,E)= \\
&\int_0^\infty dE'\int_0^{2\pi}d\varphi'\int_{-1}^{+1}d\mu'\sigma_s(\vec{r},E'\to E,\mu_s)\psi(\vec{r},\mu',\varphi',E') \\
&+F(\vec{r},\mu,\varphi,E)
\end{aligned} \tag{1}$$

The first two terms are the Fokker-Planck operators. The energy operator (first term) and the angular operator (second term) represent continuous slowing-down (CSD) and continuous-scattering (CS), respectively. The restricted stopping power, β(E), is defined in equation 2 where σ_{sing} represents the singular part of the cross section. In equation 3, T(E) is defined in terms of the restricted momentum transfer, α(E) (equation 4). The remaining terms make up the Boltzmann equation with the final term representing an inhomogeneous source[3].

$$\beta(E)=\int_0^E 2\pi\int_{-1}^{+1}\sigma_{\sin g}(E\to E',\mu_s)(E-E')d\mu_s dE' \tag{2}$$

$$T(E)=\frac{\alpha(E)}{2} \tag{3}$$

$$\alpha(E)=\int_0^E 2\pi\int_{-1}^{+1}\sigma_{\sin g}(E\to E',\mu_s)(1-\mu_s)d\mu_s dE' \tag{4}$$

The DOORS-3.2 package includes ANISN, DORT, TORT, GIP, and GRTUNCL3D[2]. Though the codes in DOORS-3.2 were originally designed to solve only the standard multi-group neutral-particle transport equation, it is possible that the transport codes might be able to accurately handle charged particle transport without modification to the solution method if cross sections are defined in a manner that accounts for the CSD term[4].

METHODOLOGY

Systems and Sources

Two basic problems were solved, (1) a homogeneous water cube of density one involving a small, isotropic source normalized to one and (2) a series of varying density 1-D water layers representing a lung phantom with a similar source. Three sets of source particles (primary and secondary) were used: photon only, photons which generate electrons and electrons only.

Cross Sections and Computations

The photon and electron cross sections were generated using CEPXS-BFP, which creates standard photon cross sections and for electrons treats the CSD operator directly and the CS operator indirectly. The cross sections were processed with ARVES, a code included with CEPXS-BFP, which transforms the direct treatment of the CSD term to indirect treatment[3]. GIP was used to convert the cross sections to the format required by the DOORS-3.2 codes. The first 40 energy groups from the Vitamin B6 library were used for the photon group structure and a 40 group linear structure over the same energy range was used for the electron group structure[5]. For the TORT cases an uncollided flux plus a first-collided source were generated with GRTUNCL3D. Finally ANISN (1-D), DORT (2-D), and TORT (3-D) were used to compute fully collided fluxes and energy deposition. TORT was used to solve problem (1) using

only photons, only electrons, and photons generating electrons. DORT was used to solve problem (2) using photons generating electrons. ANISN was used to solve problem (2) using photons generating electrons. In all cases Legendre polynomials of order nine were used for the scattering expansion. EGSnrc was used for the reference cases[6].

RESULTS

ANISN Results

Previous work for problem (2) found that fluxes from ANISN were within 4.4% of EGSnrc values when an S16 quadrature and 4mm mesh size were used and that increasing quadrature order and decreasing mesh size had little effect on the accuracy of the solution; the ANISN fluxes obtained with an S64 quadrature and 1mm mesh size were within 4.2%[7]. These results were used to compute the energy deposition. The ANISN result matched the shape of the EGSnrc result, but was higher by a factor of about 3.8. The discrepancy in the energy deposition is probably due to the treatment of the kerma factors and needs further investigation.

DORT Results

A 2-D extension of the 1-D problem analyzed with ANISN was used to test DORT's ability to transport electrons. The DORT photon flux in most voxels had errors of less than 5% compared to EGSnrc, and the largest error was within 10%. The DORT electron flux, however, generally overestimated the EGS flux by about 10% (i.e., the ratio DORT-to-EGS for the electron flux oscillated around 1.10). The normalization problem noticed for the energy deposition in the ANISN calculation persisted for the DORT case as well, confirming that the kerma factors need further investigation.

TORT Results

In the case of a photon only calculation for problem (1), the TORT flux agreed well with the flux obtained using EGSnrc. When the photon source which generates electrons was used for the same problem, the photon fluxes still agreed but the electron fluxes did not. A source of only electrons was then used where the initial energy of the electrons was varied by group. A source energy in groups 1 through 5 resulted in a non-zero flux only in groups 1 through 5 and in group 40; EGSnrc generated flux in every group. If the source energy was beyond group 5 then there was flux in every group beyond the source group, but the total flux did not agree with EGSnrc. In each circumstance TORT calculated disproportionately high flux in group 40. This anomaly may be due to oscillations in the TORT electron solution. These results, coupled with the DORT results, suggest that the electron cross sections (a) are too large for the transport methods to give accurate answers in multi-D; (b) are erroneous due to processing with CEPXS-BFP; or (c) large anisotropy might have made the Pn scattering approximation too inaccurate.

CONCLUSIONS

There is promise in continuing to investigate the use of discrete ordinates for RTP. ANISN accurately produced photon and electron fluxes, but overestimated the energy deposition; DORT overestimated the electron flux and showed the same energy deposition trend as ANISN; TORT exhibited strange group behavior of the electron flux. The DOORS package proved to be able to handle some aspects of the charged particle transport, but also showed limitations. Future work could involve using the DOORS package and CEPXS-BFP as a foundation to develop a new code that incorporates the BFP formula for treating charged particles.

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