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.

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 (equation 1).

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

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[1].

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

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

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

The DOORS-3.2 package developed by Oak Ridge National Laboratory was used for this work and 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[3].

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 treats the CSD operator directly and the CS operator indirectly for electrons. The cross sections were processed by ARVES, a code included with CEPXS-BFP, which transforms the direct treatment of the CSD term to indirect treatment [1]. GIP was used to convert the cross sections to the format required by DOORS 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[4]. For the TORT cases GRTUNCL3D was used to generate an uncollided flux plus a first-collided source. 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. Legendre polynomials of order 9 were used for all cases. EGSnrc was used for the reference cases[5].

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%[6]. These results were used to compute the energy deposition which gave an ANISN result that 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 photon flux agreed relatively well with ANISN, but the electron flux did not. The energy deposition normalized to the maximum value, however, did compare well with the EGSnrc results. The largest discrepancies were in the low density voxels (up to 20%) but in general the DORT energy deposition curve follows the EGSnrc reference.

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 fluxed did not. For the electron only source 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, where EGSnrc had 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. In both cases group 40 had disproportionately high flux. This anomaly may be due to oscillations in the TORT electron results. This fact, coupled with the DORT results, suggests 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 work on using discrete ordinates for RTP. ANISN was able to produce accurate photon and electron fluxes, but overestimated the energy deposition; DORT gave good energy deposition but incorrect electron flux; 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 may incorporate the BFP formula for treating charged particles.

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