INTRODUCTION

Recent pre-clinical and clinical studies indicate that irradiation within the dose range of 15 to 30 Gy can reduce the rate of restenosis in patients who have undergone an angioplasty (Nath 1999, King 1998). Several delivery systems of intravascular brachytherapy have been developed to deliver doses within this range with minimal normal tissue toxicity. One of the possible intravascular irradiation techniques, introduced by Amols and colleagues, is the use of filled balloon with radioactive solution (Amols et al. 1996). This method has the advantage of accurate source position and a uniform dose to the vessel wall. However, it has a potential of radiological toxicity from the radioactive liquid due to the risk of balloon rupture about 0.1% (Amols et al. 1996), since most commonly available beta emitters e.g. $^{90}$Y, $^{32}$P, $^{166}$Ho are bone seeking compounds (Amols et al. 1996).

$^{188}$Re ($E_{\beta_{max}}$=2.12 MeV , half-life=16.9 h) and $^{186}$Re ($E_{\beta_{max}}$=1.07 MeV , half-life=90.6 h) as Perrhenate or DTPA form rapidly excreted...
via the kidneys in the event of the material leaking into the systemic circulation (Lee et al. 2002). Therefore the technique utilizing the balloon filled with $^{188}$Re or $^{186}$Re have been suggested for intravascular brachytherapy.

$^{188}$Re and $^{186}$Re has dominant $\gamma$ components with 155 keV (abundance 15%) and 137 keV (abundance 9%), respectively. These $\gamma$ components can be used for imaging purposes.

$^{188}$Re is supplied as an $^{188}$W / $^{188}$Re generator, the half life is long enough for experimental purposes (Knapp et al. 1999). An ion exchange column-based method used to concentrate $^{188}$Re to 100 mCi/ml but $^{188}$W production requiring high flux of thermal neutron must be more than 10$^{14}$ n/cm$^2$ (Hashimoto et al. 1999).

$^{186}$Re with the thermal neutron capture cross section, 112±0.2 barn, is produced by reactors using flux of thermal neutron about 10$^{13}$ n/cm$^2$, (Hashimoto et al. 1999).

Dose distribution of $^{90}$Y solution loaded into a balloon of 3mm diameter has been presented by Amols et al. (1996), and dosimetry of $^{188}$Re-DTPA for endovascular intra-balloon brachytherapy has been performed by Lee et al. (2002).

In this study, the possibility of using $^{188}$Re or $^{186}$Re solution for endovascular brachytherapy is investigated and the comparison of dose distributions around balloon that filled with $^{188}$Re or $^{186}$Re solution were performed using Monte Carlo simulation.

**MATERIALS AND METHODS**

**Dose distribution calculation around the balloon with Monte Carlo simulation**

The dose distribution due to a radioactive liquid filled balloon by numeric integration of a Monte Carlo generated point kernel over the volume of the balloon, (Amols et al. 1996) is as follows:

$$D(p) = \int k(r') (A/v) dv; \quad (1)$$

Where $D(p)$ is the dose rate in (Grays per second) at point P.

$k(r)$ is dose point kernel in (Grays per decay), $r'$ is radial distance in cm, $A/v$ is activity per unit volume in (becquerels per cm$^3$), and $k(r')$ is defined as a dose point kernel, corresponding to the expected value of dose per gram of tissue delivered at point $r'$ by a unit point source of $^{188}$Re located at r, (Amols et al. 1996).

In figure 1, a schematic diagram of dose calculation for a point $P(x, y, z)$ on a balloon with external radius of $R_o$, and axial length of $L$ which is filled with a $\beta$ emitter radionuclide is shown. The central channel of catheter contains a lumen of radius $R_i$ to allow passage of guide wire.

**Figure 1.** Schematic diagram of dose calculation for a point $P(x, y, z)$ on a balloon with external radius of $R_o$, internal radius of $R_i$ and axial length of $L$.

In figure 2, a catheter of balloon angioplasty with a length of 40mm, diameter of 3mm, a lumen to house guide wire and a liquid entrance to send radioactive solution into balloon is shown.

**Figure 2.** A balloon catheter with four main segments: balloon, catheter body, liquid entrance and guide wire entrance.
The Monte Carlo N-particle Transport Code (MCNP4b) is used to calculate the dose rate distribution in the tissue, equivalent material around the $^{188}\text{Re}$ and $^{186}\text{Re}$ liquid source (Briesmeister 2000). The code is able to consider photoelectric, coherent, Compton and pair production interaction processes. The condensed-history electron transport algorithms in the Monte Carlo code MCNP4c are derived from ITS 3.0, which is a well–validated code for coupled electron photon simulation (Chart 2002). Differences of up to 30% have recently been reported between beta dose distributions calculated with the MCNP4b and two others other codes namely EGS4 and EGSnrc, (Wang and Li 2001). The mass absorption coefficients of Hubbel and Seltzer distributed by NIST are used to obtain the absorbed dose from energy flux (Hubble and Seltzer 1995).

Beta spectrums of $^{188}\text{Re}$ and $^{186}\text{Re}$ for using in INP file of the MCNP code were adopted from Simpkin and Makie (1990).

The source was virtually placed in the center of a cylindrical volume of tissue equivalent phantom. Considering that the source has a symmetric structure, the circular annulus tally cells around the source longitudinal axis were employed to score the eligible events. In this study, up to $1 \times 10^7$ betas was involved in each simulation. The statistical uncertainties were found to be less than 5% for all tally points.

The cylindrical approximation for the individual balloon was made to allow the use of circular symmetry in the Monte Carlo calculation resulting in a reduction in computation time. For calculation we assume that the source was uniformly distributed within the balloon volume.

**Absorbed dose calculation by MIRD schema**

Schematic of Medical Internal Radiation Dose (MIRD) for homogeneous distribution of radionuclide in a lesion is used for mean organ absorbed dose calculation due to internal distribution (Israel et al. 2000). This technique is used to calculate the absorbed doses to the surrounding organs and tissues, when a radionuclide is injected inside the body. These doses are dominated by short-range $\beta$ particles and conversion electrons.

Source organ is the same as target organ and very low contributions of the $\gamma$ emissions and X-rays are ignored.

MIRD equation (Israel et al. 2000) used in this case is:

$$D (\text{Gy}) = C_v \Sigma \Delta_i \quad (2)$$

Where, $C_v$ is an indication of the cumulative concentration in [(MBq/\text{gr}) $\text{h}$], and $\Delta_i$is the mean energy for each type of decay (charge particles or photons) in unite of [(Gy $\text{gr}$/MBq $\text{h}$)]. Values of $\Sigma \Delta_i$ for the emitted charged particles of $^{186}\text{Re}$ and $^{188}\text{Re}$ are obtained 0.198 and 0.487, respectively from ENSDF Decay Data in the MIRD (USDOE 2004).

**RESULTS**

**Dose Distribution around the balloon**

In figure 3, a point kernel dose for $^{188}\text{Re}$ and $^{186}\text{Re}$ point sources in [(cGy/s) per (Bq/ml)] was calculated. The results indicate the effective range of $^{186}\text{Re}$ was about 3 mm, but the effective range of $^{188}\text{Re}$ was more than 3 mm. The bremsstrahlung dose was less than 1% of beta particle dose for $^{188}\text{Re}$ and $^{186}\text{Re}$.

![Figure 3. Point kernel dose for $^{188}\text{Re}$ and $^{186}\text{Re}$ point sources in [(cGy/s) per (Bq/ml)].](image)

Depth dose rate distribution in [(cGy/min) per (mCi/ml)] in z=0 plane was calculated for the $^{188}\text{Re}$ and $^{186}\text{Re}$ solution in balloon with the diameter of 3 mm and length of 20 mm.

The ratio of dose rate of $^{188}\text{Re}$ to $^{186}\text{Re}$ was found to be about 3 in distance of 2 mm from the balloon center (distance of 0.5 mm from balloon surface), (figure 4).
Minimum of required activities of $^{188}$Re and $^{186}$Re were obtained 100 mCi/ml and 250 mCi/ml respectively, because delivery of doses must have been considered between 12 to 20 Gy in 4 min time (figure 5).

Table 1. Values of dose rate in depth of 0.5 mm from balloon surface for the balloon with 20 mm in length and various diameters.

<table>
<thead>
<tr>
<th>Diameter of balloon (mm)</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dose rate (Gy/min) for $^{188}$Re (100 mCi/ml)</td>
<td>2.75</td>
<td>3.65</td>
<td>4.73</td>
<td>5.33</td>
<td>5.73</td>
</tr>
<tr>
<td>Dose rate (Gy/min) for $^{188}$Re (250 mCi/ml)</td>
<td>2.43</td>
<td>2.88</td>
<td>3.25</td>
<td>3.33</td>
<td>3.45</td>
</tr>
</tbody>
</table>
The effects of various balloon lengths vs. depth dose rate were evaluated (table 2).

Table 2. Dose rate in 0.5mm depth from balloon surface with diameter of 3mm and lengths of 20mm, 40mm.

<table>
<thead>
<tr>
<th>Liquid source</th>
<th>Re-188, 100mCi/ml</th>
<th>Re-186, 250 mCi/ml</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balloon specification</td>
<td>L= 20 mm</td>
<td>L= 40 mm</td>
</tr>
<tr>
<td>Dose rate (Gy/min)</td>
<td>2.88</td>
<td>3.11</td>
</tr>
</tbody>
</table>

Dose rate in unit of (Gy/min) in depth of 0.5mm from balloon surface was calculated for the balloon with diameter of 3mm and lengths of 20mm, 40mm. Results indicate that there was a little increment in dose rate, about 2%, for 188Re and 7% for 186Re when the length of the balloon increased from 20mm to 40mm.

MIRD

Results of calculation for internal dose assessment of 186Re-DTPA from data of Israel et al. are shown for the whole body and bladder in table 3. (Israel et al. 2000)

Table 3. Estimated absorbed dose from 186Re-DTPA and 188Re-DTPA, and comparison with the estimated radiation dose 99mTc-DTPA from as reported in the literature.

<table>
<thead>
<tr>
<th>Organs</th>
<th>Estimated radiation dose (mGy/MBq)</th>
<th>188Re-DTPA</th>
<th>99mTc-DTPA</th>
<th>186Re-DTPA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bladder</td>
<td>Results from data of Israel et al. 2000</td>
<td>1.96</td>
<td>2.71</td>
<td>4.56</td>
</tr>
<tr>
<td>Whole body</td>
<td>0.0024</td>
<td>0.012</td>
<td>0.0056</td>
<td></td>
</tr>
</tbody>
</table>

Estimated doses to the whole body and bladder have been measured by Lee and colleagues (Lee et al. 2002).

Internal dose of 99mTc-DTPA model for the whole body and bladder has been found to be 0.012 and 2.71 (mGy/MBq), respectively (Thomas et al. 1984).

DISCUSSION

One of the possible intravascular irradiation techniques after Balloon angioplasty is to use a radioactive filled balloon. This method may be a good alternative to the radioactive stent (Prestwich and Kennet 1995) or radioactive beta-catheter (Verin et al. 1997), because it has more dose uniformity around angioplasty balloon to the vessel wall.

32P, 90Y, 166Ho have been tried experimentally using these methods but the three isotopes are inherent bone seekers and thus rupture would be resulted in the outcome radiation damage to adjacent bone marrow (Lee et al. 2002).

188Re and 186Re with Perrhenate or DTPA form have been proposed as good candidates, because similar to 99mTc-Perrhenate, are localized in the thyroid, stomach, kidney and bladder following intravenous injection. DTPA is readily labeled with 188Re and 186Re which 188Re-DTPA and 186Re-DTPA excreted rapidily via the kidneys when injected intravenously. Upon accidental balloon rupture, the gamma ray of 188Re-DTPA (155 keV, 15%) or gamma ray of 186Re-DTPA (137 keV, 9%) would enable imaging in the event of balloon rupture.

The results of calculation for internal dose indicate that the whole body absorbed dose will be about 20 to 30 mGy, if the total amount of 100mCi (3700 MBq) of 188Re-DTPA or 250mCi (9250 MBq) of 186Re-DTPA leaks into the systemic circulation. However, the probability of a balloon rupture is small, as inflation pressures used for intravascular radiation therapy are lower than those used in the practice of angioplasty, then the risk of internal irradiation dose would be lower than the above calculations in practice.

The calculated activity for the 188Re is in line with the dosimetry results obtained by Lee et al. (2002), and there were some differences about 12% in comparison with results reported by Stabin et al. (2000). They had been employed the EGS4 code for calculating the beta particles doses in which the calculated activities for delivering a dose of 30 Gy in 5min at 0.5mm
from the vessel surface were $^{186}\text{Re}$, 17000 MBq/ml (460 mCi/ml); $^{188}\text{Re}$, 7000 MBq/ml (190 mCi/ml); (Stabin et al. 2000).

It should be noted that there are some uncertainties for using the calculated doses in clinical practice in general. The artery wall was considered as a tissue equivalent material. If the artery was assumed to have a deposition of plaque around the inside wall of artery, doses on the plaque side of the vessel would be lower than on the nonplaque side. Plaque depositions were not generally distributed symmetrically throughout the vessel wall, being irregularly deposited over some or the entire wall; it was not possible to consider plaque geometries in computer simulations.

There was some dose drop-off about 50% near the ends of balloon, so, the length of the balloon must have be selected longer than length of target in artery about 20%.

Finally, it must be noted that, there are certain inevitable limitations of the modeling process in approximating physical realities. In clinical situation, physicians may counter many different artery geometries, plaque deposition configuration, plaque compositions, etc. Therefore, interpreting the results for using in a clinical study should be considered carefully.

REFERENCES


Hashimoto K., Musidja M.Y., Motoshi S., Kobayashi K., Izumo M. (1999). Production of $^{186}\text{Re}$ and $^{188}\text{Re}$ and synthesis of $^{188}\text{Re}$-DTPA. JAERI-Conf. 99/006.


and Isotopes, 57: 657-664.

USDOE (2004). ENSDF decay data in the MIRD format. National Nuclear Data Center, Brookhaven National Laboratory, Upton, N.Y., USA.