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Estimation of dose distribution in occupationally exposed individuals to FDG-^{18}F

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ABSTRACT

The use of unsealed radiation sources in nuclear medicine can lead to important incorporation of radionuclides, especially for occupationally exposed individuals (OEIs) during production and handling of radiopharmaceuticals. In this study, computer simulation was proposed as an alternative methodology for evaluation of the absorbed dose distribution and for the effective dose value in OEIs. For this purpose, the Exposure Computational Model (ECM) which is named as FSUP (Female Adult Mesh - supine) were used. This ECM is composed of: voxel phantom FASH (Female Adult MeSH) in the supine position, the MC code EGSnrc and an algorythm simulator of general internal source. This algorithm was modified to adapt to specific needs of the positronic emission from FDG-18F. The obtained results are presented as absorbed dose/accumulated activity. To obtain the absorbed dose distribution it was necessary to use accumulative activity data from the *in vivo* bioassay. The absorbed dose distribution and the

value of estimated effective dose in this study did not exceed the limits for occupational exposure. Therefore, the creation of a database with the distribution of accumulated activity is suggested in order to estimate the absorbed dose in radiosensitive organs and the effective dose for OEI in similar environment.

Keywords: EGSnrc, OEI, FDG-18F

1. INTRODUCTION

The use of nuclear technology has grown considerably in numerous areas, increasing the production of radioactive sources and the number of occupationally exposed individuals (OEI) subjected to radionuclides. The absorbed dose resulting from the use of ionizing radiation could imply biological effects in workers. Therefore, its accurate estimation is essential for radioprotection of the OEIs.

In nuclear medicine, the use of open radiation sources can lead to significant incorporation of radionuclides, especially during the production and handling of radiopharmaceuticals procedures [1]. The radiopharmaceutical FDG-^{18}F is the positron emitter most currently used in PET scans (Positron Emission Tomography). It is routinely produced at *Divisão de Produção de Radiofármacos (DIPRA), Centro Regional de Ciências Nucleares do Nordeste (CRCN-NE/CNEN)*, where the methodology for internal monitoring of OEIs was implemented through *in vivo* bioassay technique [2]. The incorporated activity data resulting from this technique was used to obtain the distribution of absorbed dose.

The *in vivo* bioassay technique is recognized as a valuable tool in radioprotection as well as in dosimetry [3] and is characterized by the positioning of radiation detectors near to the predefined body regions. This technique allows to identify and locate the radionuclides present in the body at the moment of measurement, and to estimate the absorbed dose by the determination of incorporated activity.

The absorbed dose is related to the accumulated activity in the source organs. The values of absorbed dose can not be measured directly in an exposed individual and direct measurements with radiation detectors are practically restricted to the body surface [4]. Therefore, exposure computational models (ECM) are used to calculate the dosimetric quantities of interest and to evaluate the effect of the radiation produced in the environment. The ECM is composed of an:

1) Algorithm for radioactive sources:
To generate the initial state of the particles it is necessary simulate the type of radioactive source of interest. The variables that compose the initial state (which will be implemented by the source algorithm) are: energy and initial particle position (x, y, z) and the initial direction of flight ($\cos\alpha$, $\cos\beta$, $\cos\gamma$) [5].

2) Phantom:
The phantoms used in computational dosimetry are predominantly constructed from stacks of magnetic resonance imaging (MRI) or of computed tomography (CT) (obtained from real patients scanning) or using specific software for 3D modeling. These phantoms possess the necessary anatomical realism to simulate human organs and tissues and to obtain satisfactory dosimetric results.

3) Monte Carlo code:
For use in numerical dosimetry the phantom requires the coupling to the MC code. The MC methods can be defined as statistical methods of simulation, where a statistical simulation is defined as any technique that utilizes random numbers sequences somewhere in the approached problem [6].

This paper shows an alternative methodology used to obtain the dosimetric evaluation by experimental measurements from *in vivo* internal monitoring of OEIs data and computational simulations using an ECM is presented.

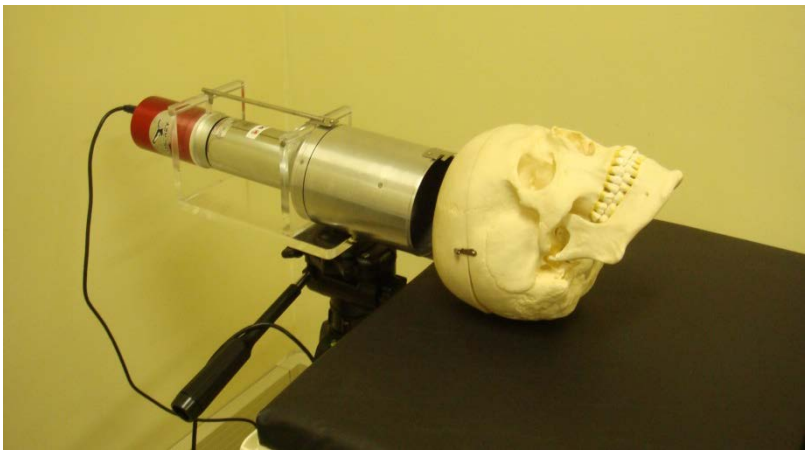
2. MATERIALS AND METHODS

2.1. Experimental Measurements Using The *In Vivo* Bioassay Method

The experimental data presented in this paper were obtained by individual monitoring for internal exposure, according to the methodology implemented at *DIPRA/CRCN-NE/CNEN*. The scintillator detector used in the *in vivo* bioassay technique was the 3" x 3" NaI(TI), model 802, manufactured by Canberra, connected to a compact module, Unispec, and controlled by the data acquisition system, Genie 2000 software.

For calibration, a simulation of a contaminated individual was performed using a brain geometry (artificial skull resin), containing standard solution of Sodium-22, placed 3 cm from the detector, as shown in Figure 1. This geometry was chosen due to the high absorption of FDG-^{18}F by the brain.

Figure 1: Positioning of the phantom in relation to the detector (indicative arrow)



Source: The author

The *in vivo* measurements were performed on seven volunteers OEIs with duration of 15 minutes each, shortly after synthesis and quality control of the radiopharmaceutical FDG-^{18}F procedures. The OEIs were kept in a supine position with the NaI(Tl) detector in the same geometry utilized to the calibration procedure, as shown in Figure 2.

Figure 2: OEI positioning in relation to the detector

Source: The author

150 measurements were performed in this geometry within 60 days of individual monitoring of internal exposure. In all measurements, seven accidental incorporations were found, resulting in the average incorporated activity of 38.3 MBq.

2.2. Simulations Using Exposure Computational Model

Based on the average incorporated activity obtained by *in vivo* bioassay in OEIs at *DIPRA/CRCN-NE/CNEN*, simulations were performed at the *Laboratório de Dosimetria Numérica (LDN), Instituto Federal de Pernambuco (IFPE)*. For this purpose, ECM were used to obtain the distribution of the absorbed dose and the value of the effective dose.

In this paper, the ECM were composed by the MC code EGSnrc (Electron Gamma Shower) [7], the voxel phantom in supine position FSUP (Female SUPine) [8] and a modified algorythm simulator of general internal source.

The EGSnrc (expanded and improved version of the EGS4 package) supports Mortran programming language and it is a package for MC simulation of photon-electron coupled

transport. It was used to run the FSUP phantom, available on *www.caldose.org* and used in its acquired original format. The algorithm simulator of internal source has been adapted to simulate the positronic emission from the radionuclide ^{18}F.

To characterize the photons source, if-else conditions were placed to separate cycles of photons (pair order from odd order). To raffle opposite directions for each type of cycle, cosine directors were allocated to maintain the position as well as direction and to reverse the emission directions of two consecutive 511 keV photons. The partial modification is shown in Figure 3.

Figure 3: Modification to characterize the photons source

FSUP.mortran

```
"-----------------------------------------------------------------------"
"STEP 1:  USER-OVERRIDE-OF-EGSnrc-MACROS                                "
"-----------------------------------------------------------------------"
$IMPLICIT-NONE;

REPLACE {$INTEGER} WITH {integer*4}
REPLACE {$REAL} WITH {DOUBLE PRECISION}

$INTEGER IRIN,I,J,NREG,NPLAN,NELIM,L,NMIL,NMIO,IONEW,IPP,IT,LNBLNK1,JJ,
         NSORG,K,IE,NTEMP,NCMIN,NCMAX,NRMIN,NRMAX,NSMIN,NSMAX,ISET,M,NSEL,
         NRSPEC,NERG,ISTEP,NRLINE,NLIN,LA,LE,MPI,NFACE,KEYX,IG,NP,
         NSPC,NXTEMP,NYTEMP,NZTEMP,NXNEW,NYNEW,NZNEW,NTIMES,imic,
         IOTEMP,ICHAVE_PET,KMAT,KAF,BSC,ICOM;

$REAL XIN,YIN,ZIN,UIN,VIN,WIN,UIN0,VIN0,WIN0,WTIN,EUC,PUC,XS,YS,ZS,FW,
      ENERIN,RFIELD,DAX,FH,RDISK,EINS,REST,QD,PI,PI2,FWH,FHH,
      XINZ,YINZ,ZINZ,XINZ0,YINZ0,ZINZ0,DTH,XMAX,YMAX,
      ZMAX,FGR,DIAG,THDIAG,DIFRD,ANGX,ANGY,FLAG,XX,YY,PROBX,PROBY,SUMXY,
      XI,XF,YI,YF,ZI,ZF,ZZ05,ZZ06,R0,Z0,RMAX,PHIM,B,ZZ03,ZZ04,CTE1,ZZ0Z,
      R,THETA,XR,YR,ZR,XMIN,ZMIN,Z1,RD,XD,YD,ZD,YMIN,XMAXH,XC,YC,ZC,EXC,
      FOCUS,XH,YH,XLIM,YLIM,ZLIM,TERMX,TERMY,CTE2,RCY,DHH,DH,HCY,PROBA1,
      PROBA2,ZZPB,ZZTH,ZZ0R,ZZ02,ZZC1,ZZC2,PSI,DZ,RT,XT,YT,ZT,RMIN,RC2,DAY,
      RC3,FACTOR,AA1,AA2,XX0,DXX,PBASE,THDISK,PROB1,RTEST,HIP,WINF,FLAGX,
      FLAGY,ZZ07,ZZ0X,ZZ0Y,RNDX,RNDY,RNDZ,ZZ08,ZZ09,RAC,ESPM,RDIS,ZZ01,DAZ,
      ECS6,ECS7,ECS10,ECS11,XSPO,YSPO,ZSPO,DIX,DIY,DIZ,AA,HH,LAMBDA,YY1,FFX,
      AELIPSE,BELIPSE,CELIPSE;
```

Source: The author

It was necessary to double the number of histories in order to simulate the photon transport in the positronic emission of the radioactive source, as shown in Figure 4.

Figure 4: Modification in the source algorithm performed in order to adapt to the needs of positronic emission

FSUP.mortran

```
697
698   ISET=0;
699   XS=XQ(IE);          "PARAMETER TRANSFORMATION FOR EACH EXPOSURE SET-UP"
700   YS=YQ(IE);          "IN LOOP NELIM"
701   ZS=ZQ(IE);
702   FW=FWQ(IE);
703   FH=FHQ(IE);
704   RDISK=RQ(IE);
705   YIELD=YIQ(IE);
706   IGEON=IGEQ(IE);
707   NTIMES=2*NTIQ(IE);
708   NRSPEC=NSPQ(IE);
709   EINS=EIQ(IE);
710   FILEOUT=FILEQ(IE);
711   EUC=EC(IE);
712   PUC=PC(IE);
713   ECS6=E6(IE);
714   ECS7=E7(IE);
715   ECS10=E10(IE);
716   ECS11=E11(IE);
717   ALT=ALTQ(IE);
718   IF(ALT.LT.20)[ALT=20.;]
719   IF(ALT.GT.80)[ALT=80.;]
```

Source: The author

After the changes made in the source algorithm, the EMC were properly organized in specific directory as "C:\HEN_HOUSE\EGS_HOME". To simulate an accidental incorporation case of FDG-^{18}F by OEIs, it was necessary to choose the optimal number of histories, which ranged from 1×10^5 to 1×10^8 and to perform other modifications in the standard input file EGSINP, as shown in Figure 5.

Figure 5: Modifications done in the standard file EGSINP. In spotlight, energy and ID values are corresponding to the brain, respectively

FSUP_N_PET.egsinp

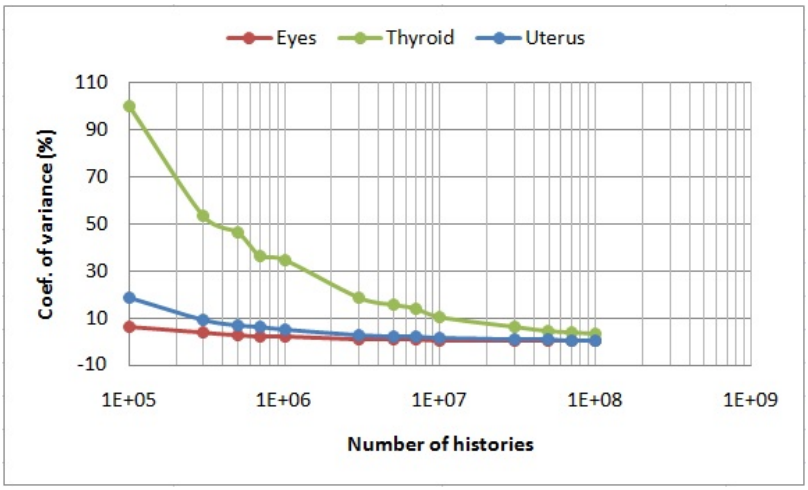
```
1  DATA INPUT FOR EGSnrc/FASH3_MICR0160 CODE FOR INTERNAL/EXTERNAL WHOLE BODY EXPOSURES
2  micro
3  MACRO VOXEL DIMENS.  [cm]:  0.12  0.12  0.12
4   13
5  WHOLE BODY EXPOSURE FROM AN INTERNAL EMITTER IN THE BRAIN - FDG-18 - PET
6  XS,YS,ZS,FW,FH,RQ,YIQ    :     31.32 -10000.00     81.36     62.64    162.72   2000.00      1.00
7  NTIM,IGE,NSPEC,EIN,NG,NUM:    100000  14   0    511.   4   8   3   8   1   0   1   0   0   1
8  IQ,ECT,PCT,WT,EC6,7,10,11:   0   20.    2.  1.00    5.    5.    5.    5. 0.60 0.70 0.25 0.48 0.38 35.0
9  RESULTS IN FILE          :FSUP_1E5_PET_FDG
```

Source: The author

3. RESULTS AND DISCUSSION

The MC code EGSnrc provides output data of dose/accumulated activity in the source organ for a list of organs. From this list, three radiosensitive organs were analyzed (eyes, thyroid and uterus) for choose the ideal number of histories (5×10^7) by means of coefficient of variance. In order to estimate satisfactorily the simulation accuracy, this value could not exceed 5%, as shown in Figure 6.

Figure 6: Coefficient of variance for eyes, thyroid and uterus due to the increase in the number of histories



Source: The author

From the selected number of histories, it was possible to obtain results for dosimetric evaluations, which were presented as the ratio of absorbed dose to accumulated activity (mGy/MBq.s). To obtain the absorbed dose distribution in organs, as shown in Table 1, it was necessary to estimate the accumulated activity, which was 29.1 MBq.s, according to Equation 1 [9].

$$\tilde{A}_h = 1{,}443 \cdot A_h \cdot f \cdot t_{1/2eff} \quad (1)$$

Where:

$\tilde{A}_h$ = Accumulated activity in organ;

A_h = Incorporated activity;

f = Fractional distribution to organ or tissue [10];

$t_{1/2eff}$ = Effective half-life.

To estimate the absorbed dose value in organs, only the accumulated activity of radiopharmaceutical in the brain was considered. According to ICRP publication 106 the biological half-life of FDG-^{18}F in brain is infinitely long, because it never clears the brain [10]. Then the physical half-life is equal to effective half-life [11].

Table 1: Sample of organs containing values of absorbed dose distribution obtained from accumulated activity and coefficients of variance respectively.

Organ	Absorbed dose/Accumulated activity (mGy/MBq.s)	Absorbed dose (mGy)	Coefficients of variance (%)
Eyes	2.5×10^{-6}	7.28×10^{-5}	0.29
Thyroid	3.1×10^{-7}	9.02×10^{-6}	0.73
Uterus	1.2×10^{-9}	3.49×10^{-8}	4.76
Brain	1.0×10^{-5}	2.91×10^{-4}	0.02
Breasts	4.1×10^{-8}	1.19×10^{-6}	0.60
Stomach Wall	1.6×10^{-8}	4.66×10^{-7}	1.05
Liver	2.2×10^{-8}	6.40×10^{-7}	0.33
Lungs	8.3×10^{-8}	2.42×10^{-6}	0.19
Small Intestine Wall	3.3×10^{-9}	9.60×10^{-8}	1.11

According to the dosimetric data for the chosen number of histories, the ratio between effective dose and accumulated activity provided by EGSnrc was 2.14×10^{-7} Sv/MBq.s. To estimate the effective dose, the estimated value of the accumulated activity was used, resulting in 6.23×10^{-6} Sv. The effective dose does not exceed the limits for female occupational exposure.

4. CONCLUSIONS

The estimated absorbed dose distribution and the value of effective dose in this paper did not exceed the limits for occupational exposure. Despite the probability of incorporation of radiopharmaceuticals being small due to safe work conditions, the OEIs can be exposed in unusual conditions, such as accident. Thus, a quantitative analysis of the distribution of energy through the absorbed dose in radiosensitive organs and tissues of OEIs is essential. As perspective a database containing the distribution of accumulated activity to estimate the absorbed and effective dose in OEIs in similar environments is going to be created.

5. ACKNOWLEDGMENT

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