Original paper

# Evaluation of BEBIG HDR $^{60}$Co system for non-invasive image-guided breast brachytherapy

Mehdi Zehtabian, PhD[1], Sedigheh Sina, PhD[1,2], Mark J. Rivard, PhD[3], Ali S. Meigooni, PhD[1,4]

[1]Radiation Medicine Department, School of Mechanical Engineering, Shiraz University, Shiraz, Iran, [2]Radiation Research Center, Shiraz University, Shiraz, Iran, [3]Department of Radiation Oncology, Tufts University School of Medicine, Boston, USA, [4]Comprehensive Cancer Centers of Nevada, Las Vegas, USA

## Abstract

**Purpose:** HDR $^{60}$Co system has recently been developed and utilized for brachytherapy in many countries outside of the U.S. as an alternative to $^{192}$Ir. In addition, the AccuBoost® technique has been demonstrated to be a successful non-invasive image-guided breast brachytherapy treatment option. The goal of this project is to evaluate the possibility of utilizing the BEBIG HDR $^{60}$Co system for AccuBoost treatment. These evaluations are performed with Monte Carlo (MC) simulation technique.

**Material and methods:** In this project, the MC calculated dose distributions from HDR $^{60}$Co for various breast sizes have been compared with the simulated data using an HDR $^{192}$Ir source. These calculations were performed using the MCNP5 code. The initial calculations were made with the same applicator dimensions as the ones used with the HDR $^{192}$Ir system (referred here after as standard applicator). The activity of the $^{60}$Co source was selected such that the dose at the center of the breast would be the same as the values from the $^{192}$Ir source. Then, the applicator wall-thickness for the HDR $^{60}$Co system was increased to diminish skin dose to levels received when using the HDR $^{192}$Ir system. With this geometry, dose values to the chest wall and the skin were evaluated. Finally, the impact of a conical attenuator with the modified applicator for the HDR $^{60}$Co system was analyzed.

**Results:** These investigations demonstrated that loading the $^{60}$Co sources inside the thick-walled applicators created similar dose distributions to those of the $^{192}$Ir source in the standard applicators. However, dose to the chest wall and breast skin with $^{60}$Co source was reduced using the thick-walled applicators relative to the standard applicators. The applicators with conical attenuator reduced the skin dose for both source types.

**Conclusions:** The AccuBoost treatment can be performed with the $^{60}$Co source and thick-wall applicators instead of $^{192}$Ir with standard applicators.

## Purpose

High-dose-rate (HDR) brachytherapy is one of the most commonly used treatment modalities in radiation therapy for various disease sites such as breast, prostate, cervix, and vagina. Presently in the U.S., there are three different HDR remote afterloading systems (Nucletron, an Elekta company, Elekta AB, Stockholm, Sweden, Vari-Source and GammaMed from Varian Medical Systems, Inc., Palo Alto, CA, USA) that utilize the $^{192}$Ir radionuclide. The $^{192}$Ir half-life is 73.81 days and the mean photon energy emission in air is approximately 0.4 MeV. Despite the great benefit of these systems in clinical procedures, its half-life limits the time period that each source can be used before it decays to the level that would not be convenient for clinical applications. This source type is typically replaced four to six times per year in the U.S. This fre-

quency is not suitable for many countries without direct access to the source vendors, as the time period for source shipment through customs and for source exchanges will further reduce the useful lifetime of $^{192}$Ir sources.

Recently, HDR $^{60}$Co systems have been introduced as an alternative to HDR $^{192}$Ir systems for countries outside the U.S., with the possible advantages of reduction of the frequency of the source exchange [1]. This radionuclide has a 5.27 year half-life and emits two gamma rays per disintegration with a mean energy of 1.25 MeV. Presently, there are three different HDR $^{60}$Co source models that are available for clinical applications [1, 2, 3, 4, 5, 6, 7, 8, 9, 10]. These systems are the model GZP6 HDR manufactured by the Nuclear Power Institute of China (Chengdu, China) [1, 2, 3, 4, 5], the Ralstron remote afterloader (Shimadzu Corporation, Japan) [6], and the BEBIG Multi-Source remote

afterloader (Eckert & Ziegler BEBIG GmbH, Berlin, Germany) [7, 8, 9, 10, 11, 12, 13, 14, 15]. These afterloaders are utilized in many countries outside of the U.S. Following is a brief description of each of these systems:

1. GZP6 HDR is composed of three different channels and contains six different source tandems [1, 2, 3]. Each source tandem is designated for a specific function through a specific channel in the HDR unit. Five out of the six sources are stationary and one source (source number 6) has stepping capabilities for the treatment of longer active lengths than the other sources. Each source is composed of a source-braid or packing that consists of one to four radioactive $^{60}$Co source pellets. These sources also consist of some non-active steel pellets. Dosimetric characteristics of these sources have been evaluated following the AAPM TG-43 recommendations [16, 17, 18] by different investigators [3, 4, 5]. The treatment planning system (TPS) permits selections of the source arrangements and prescription doses. These plans are not user-adjustable.

2. The Ralstron remote afterloader is used for treatment of patients with gynecological cancers [6]. Three different HDR $^{60}$Co source geometries have been designed that incorporate two $^{60}$Co pellets either in contact or spaced 9 mm and 11 mm apart. The dosimetric data used with this afterloader system has been obtained by Papagiannis *et al.* using Monte Carlo (MC) dosimetry techniques [6]. These authors present a complete dosimetric dataset with tabulated data in the form of 'along and away' format and following the AAPM TG-43 formalism [16, 17, 18].

3. The third HDR $^{60}$Co system was introduced by BEBIG using the model Co0.A86 source. This source is composed of a 3.5 mm long and 0.5 mm diameter central cylindrical active core that is made of metallic cobalt, containing $^{60}$Co. The active core is covered by a cylindrical stainless-steel capsule of 0.15 mm thick with a 1 mm external diameter. Dosimetric characteristics of this source design have been evaluated using the MC simulation technique following the TG-43 recommendations [7, 8, 9, 10, 11, 12, 13, 14, 15].

Although dosimetric characteristics of these sources have been evaluated using the TG-43 formalism, their clinical applications have not been fully explored, particularly in the U.S. For example, the AccuBoost technique has been introduced (Advanced Radiation Therapy, LLC, Tyngsboro, MA, USA) [19, 20, 21] for boost or accelerated partial breast irradiation (APBI) treatment modalities [22, 23] using non-invasive image-guided breast brachytherapy (NIBB) [24, 25] in contrast to other interstitial techniques [26, 27, 28, 29]. The clinical advances of this treatment technique have been demonstrated by different investigators [23]. However, application of this treatment modality is currently limited to HDR $^{192}$Ir systems.

The goal of this study was to examine the possibility of APBI treatments with HDR $^{60}$Co sources. This evaluation was performed by calculating dose distributions for both $^{60}$Co and $^{192}$Ir sources in the same breast geometry using MC simulations. Dose distributions were calculated with the standard AccuBoost applicators and also with novel applicators to achieve suitable dosimetric results with HDR $^{60}$Co sources.

## Material and methods

### Radioactive sources

For these investigations, two commercially-available HDR brachytherapy sources were considered; the micro-Selectron HDR $^{192}$Ir (model 105.002 "v2" , Nucletron, an Elekta company, Elekta AB, Stockholm, Sweden) [18, 30, 31], and the BEBIG HDR $^{60}$Co model Co0.A86 source [7, 18]. Selection of these sources was based on scientific examples for each radionuclide, and did not indicate product endorsement by the authors. Details of their design and geometric characteristics are presented below. It should be noted that the comparison of the dose rate constants and air-kerma rate constant of these sources indicate that 1 GBq of $^{60}$Co is equivalent to 2.77 GBq of $^{192}$Ir [18]. Currently, these sources are available with 370 GBq (10 Ci) for $^{192}$Ir, and 74 GBq (2 Ci) for $^{60}$Co (model Co0.A86, Eckert & Ziegler BEBIG) [32]. With the above information, 2 Ci of $^{60}$Co is equivalent to 5.54 Ci of $^{192}$Ir.

### High-dose-rate $^{192}$Ir source

The microSelectron $^{192}$Ir source has an active length of 3.6 mm with diameter of 0.65 mm (Figure 1). The source
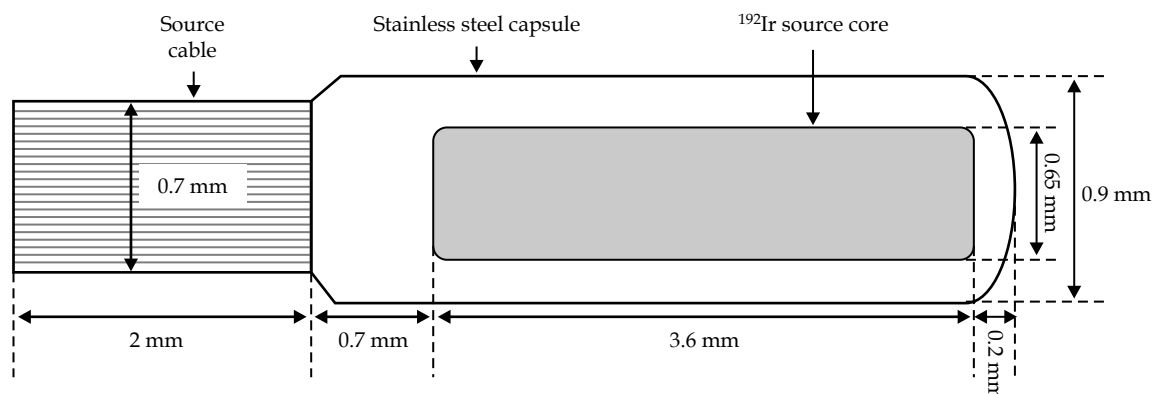


**Fig. 1.** Schematic diagram of the microSelectron-HDR $^{192}$Ir v2 source. The coordinate system is at the geometric center of the radioactive core
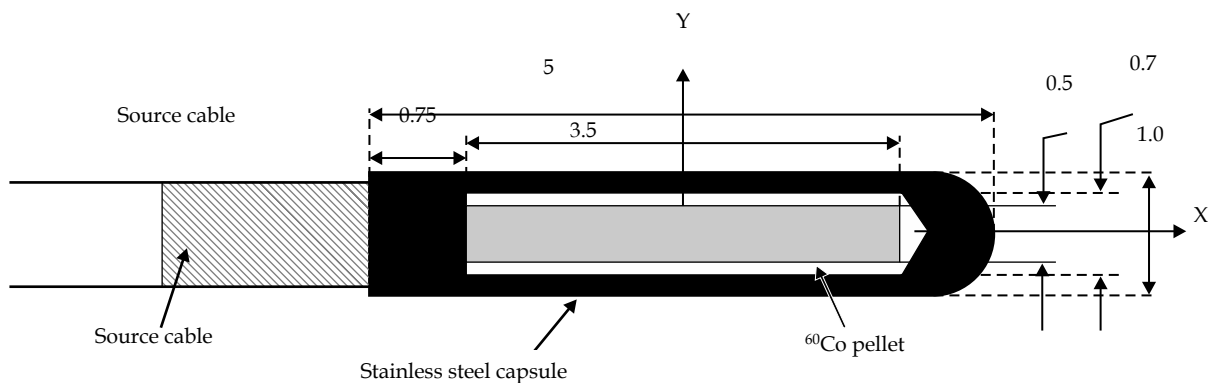
**Fig. 2.** Schematic diagram of the BEBIG HDR ^{60}Co source (model Co0.A86). Dimensions are in millimeters. The coordinate system has the origin situated in the geometric center of the active volume

core is encapsulated with an AISI 304 steel capsule, which has outer diameter 0.9 mm, inner diameter 0.65 mm, and length 4.5 mm, and is connected to a 2 m long steel cable having diameter of 0.7 mm. The thickness of the capsule on the opposite end of the steel cable is 0.2 mm and side of the iridium core toward the cable is 0.7 mm. The TG-43 dosimetry parameters for this source have been evaluated [18, 30, 31].

### High-dose-rate ^{60}Co source

The BEBIG model Co0.A86 source is shown in Figure 2. This source contains a ^{60}Co pellet having a length of 3.5 mm and a diameter of 0.5 mm, which is covered by a 0.15 mm thick cylindrical stainless-steel capsule with an external diameter of 1.0 mm. The TG-43 dosimetry parameters of this source have also been evaluated [7, 8].

### Monte Carlo calculations

Version 1.40 of the MCNP5 MC code was used to perform radiation transport simulations in these investigations [33]. Among the different tally types available in the MCNP code for scoring diverse radiological characteristics [34], the *F4 tally was used to estimate the brachytherapy dose distributions. This track-length tally provided energy flux in units MeV/cm$^2$ that was converted to absorbed dose by assuming its equivalence with collisional kerma and applying suitable $\mu_{en}/\rho$ coefficients. In these simulations, the sources were positioned within a cubic water phantom 30 cm on each side. The range of knock-on electrons was considered small for this study, so only photon transport was conducted. Spherical tally cells with radii ranging from 0.2 mm to 0.7 mm were utilized for scoring dose at different distances. The statistical fluctuations of the calculated values were diminished by increasing the tally cell size with increasing distance. The accuracy of our MC simulation techniques for brachytherapy dosimetry has been previously demonstrated [35, 36].

Figure 3 shows a simplified schematic view of the simulation geometry containing the breast tissue, chest wall, and applicators. All simulations were performed with 10$^9$ photon histories to ensure that statistical uncertainties in absorbed dose results were < 0.5%.

### Phantom and applicator geometries

MC simulations were performed with identical phantom geometries in order to compare the dose distributions delivered by the ^{60}Co or ^{192}Ir sources to the breast and the surrounding normal tissues. Figure 3A shows the position of the source within the catheter of a 6 cm diameter applicator [20]. Two applicators were positioned in a parallel-opposed manner, directing beams of collimated radiation towards the compressed breast tissue located between the two applicators. Within each applicator, 18 dwell positions were simulated (Figure 4), where source-to-source scatter would have a negligible effect on the dose outside the applicators [37]. Three sets of simulations were conducted and are described as follows:
1. The applicator and phantom geometries for the two source types were initially the same: see Figure 3A.
2. Calculated skin dose from the ^{60}Co source was evaluated, and the applicator wall thickness was increased from 6 mm to 12 mm, see Figure 3B, to reduce the chest wall dose to a comparable value from the ^{192}Ir source. The heights of the applicator (i.e. distance between the source center and open surface of the applicator) remained the same as the standard applicator from Accu-Boost (i.e. 24 mm) [20].
3. Simulations for the aforementioned applicators were repeated with the presence of a conical attenuator as in Figure 3C.

These calculations were performed assuming water as composition of chest phantom, while the breast tissue was composed of hydrogen 9.4%, carbon 61.9%, nitrogen 3.6%, oxygen 24.5%, and calcium 0.6%. A water phantom with dimension of 30 × 30 × 20 cm$^3$, was considered for the chest region. Three different compressed breast sizes were also considered in this study, including (12 × 12 × 4 cm$^3$), (12 × 12 × 6 cm$^3$), (12 × 12 × 8 cm$^3$). Therefore, the simulations were performed for compressed breast thicknesses of 4, 6, and 8 cm.

To score dose inside the breast and chest, the phantom was divided to fine cubic (0.5 cm)$^3$ tally cells (see Figure 3). In addition to dose distributions within the breast, the chest wall dose and the breast skin dose were assessed. In these simulations, the dwell times and positions of both source types were considered such that the accumulated dose to
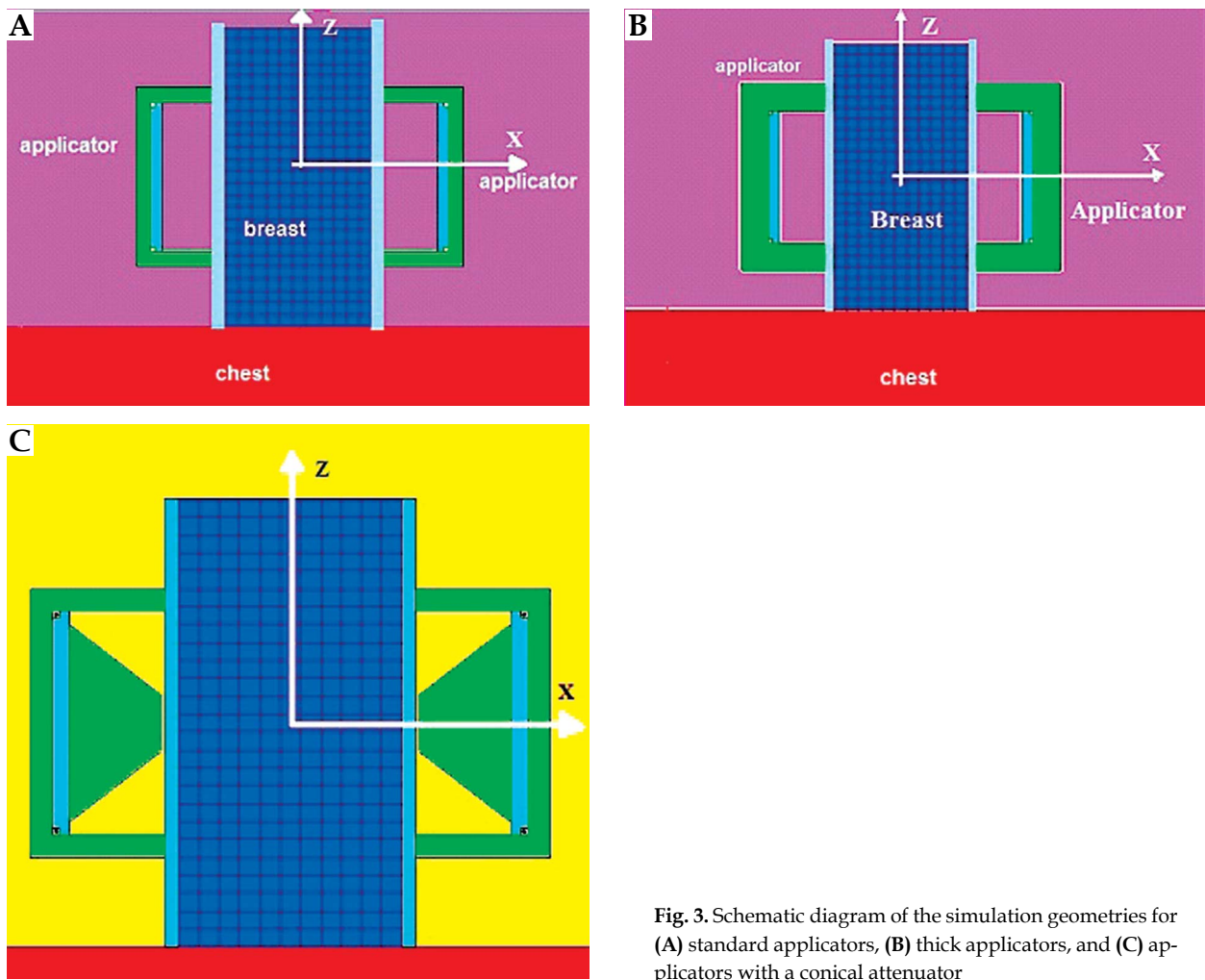
**Fig. 3.** Schematic diagram of the simulation geometries for **(A)** standard applicators, **(B)** thick applicators, and **(C)** applicators with a conical attenuator
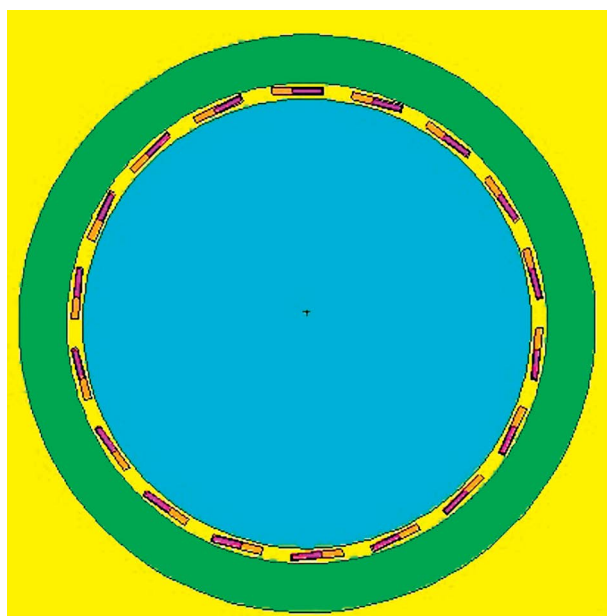


**Fig. 4.** The position of HDR $^{192}$Ir or $^{60}$Co sources inside each breast brachytherapy applicator

the center of the breast would be 3,400 cGy. The regions defined for estimating radiation dose to the breast skin and chest wall are shown in Figures 5A and 5B, respectively. As mentioned previously, these regions were subdivided into (0.5 cm)$^3$ cubic tally cells. Figure 5A illustrates the region where radiation dose to the breast skin was calculated adjacent to the compression plate.

## Results

Figure 6A shows the comparison of the 2D isodose curves, in the middle plane of the breast in XZ direction as shown in Figures 3A and 3B for HDR $^{192}$Ir and $^{60}$Co sources. These results are obtained by a 6 cm diameter standard and thick-walled applicator for a 6 cm thick compressed breast. The applicator wall thickness was increased from 6 mm to 12 mm for the HDR $^{60}$Co source to attenuate the leakage radiation. Figure 6B indicates that the resultant dose distribution from HDR $^{60}$Co source is similar to the HDR $^{192}$Ir results. Similar results were obtained for the 4 cm and 8 cm thick compressions. These results indicate that dose distributions within the treatment volume are similar for HDR $^{192}$Ir and $^{60}$Co systems. In addition, these results were not very sensitive to the applicator wall thickness.
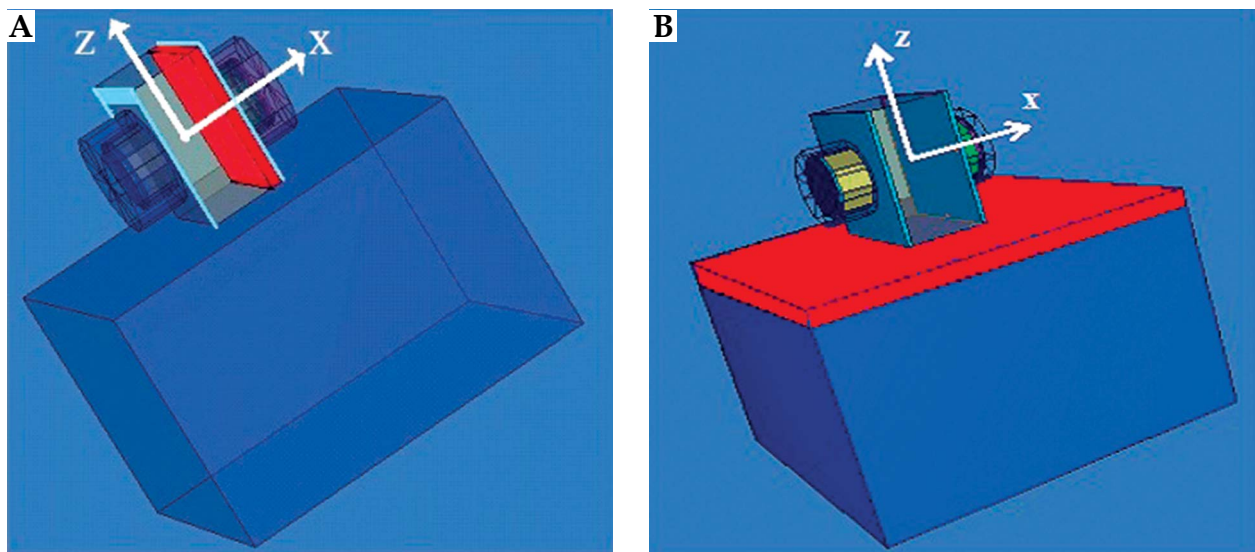
**Fig. 5.** Schematic diagram of regions used for dose estimating for **(A)** the breast skin and **(B)** chest wall. In each case, the scoring zone is colored red
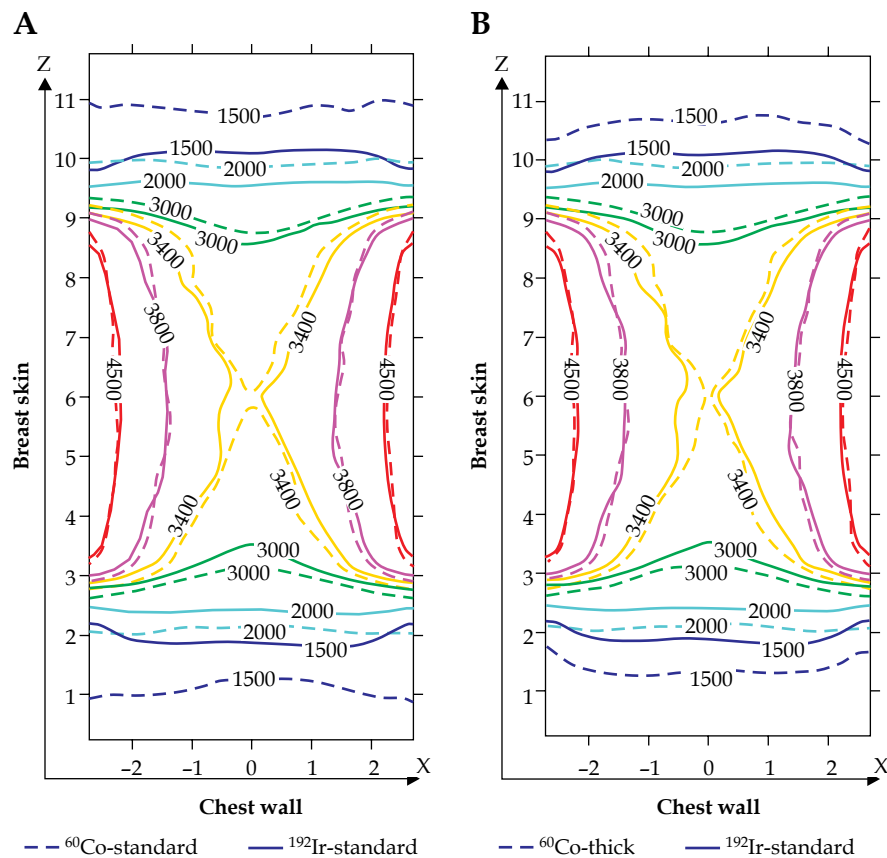


- - - $^{60}$Co-standard     — $^{192}$Ir-standard     - - - $^{60}$Co-thick     — $^{192}$Ir-standard

**Fig. 6.** Comparison of the 2D isodose distributions from HDR $^{192}$Ir and $^{60}$Co sources using **(A)** the standard 6 cm diameter AccuBoost applicator design dimensions for a 6 cm thick compression, and **(B)** the HDR $^{60}$Co results for an applicator having thicker walls in comparison to the HDR $^{192}$Ir results shown in part **(A)**

Figure 7A shows a comparison of isodose curves, in the middle plane of a 6 cm thick compressed breast in the XZ direction, as shown in Figure 3C, using the standard applicator with a conical attenuator for the two radiation sources. Figure 7B shows a comparison of 2D dose distributions for the HDR $^{192}$Ir in the standard applicator and the HDR $^{60}$Co source in the thick-walled applicator in presence of the conical attenuator. Similar results were obtained for the 4 cm and 8 cm compressions. These results also show comparable dose distributions within the treatment volume for both HDR $^{192}$Ir and $^{60}$Co sources, regardless of the applicator wall thickness. A comparison of
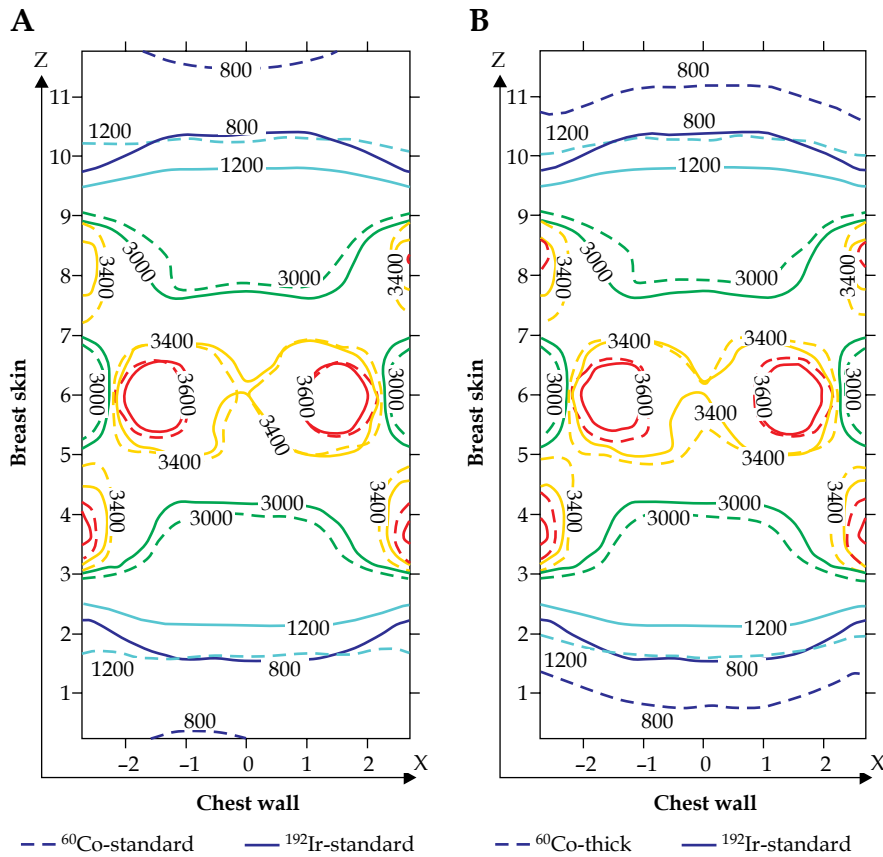
**Fig. 7.** Comparison of the 2D isodose distributions of HDR $^{60}$Co with HDR $^{192}$Ir in the presence of a conical attenuator for 6 cm thick compressed breast tissue; **(A)** using the standard AccuBoost applicators for both sources, and **(B)** the standard applicator for HDR $^{192}$Ir and thick applicator for the HDR $^{60}$Co. These results are obtained with a conical attenuator

the isodose lines in Figure 6A and Figure 6B for the HDR $^{192}$Ir and $^{60}$Co sources, could be used to assess the influence of the source type and applicator thickness on the

chest wall dose. For example, a comparison of the 15 Gy isodose lines for HDR $^{60}$Co source on Figure 6B and Figure 6A shows that this isodose line moved away from the
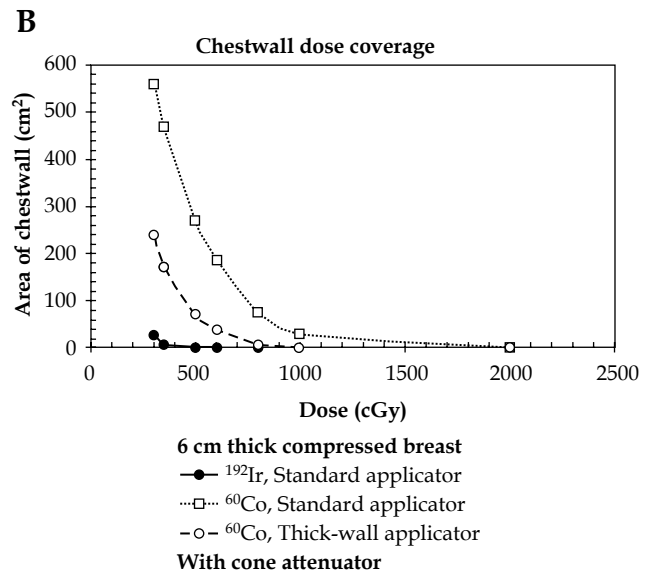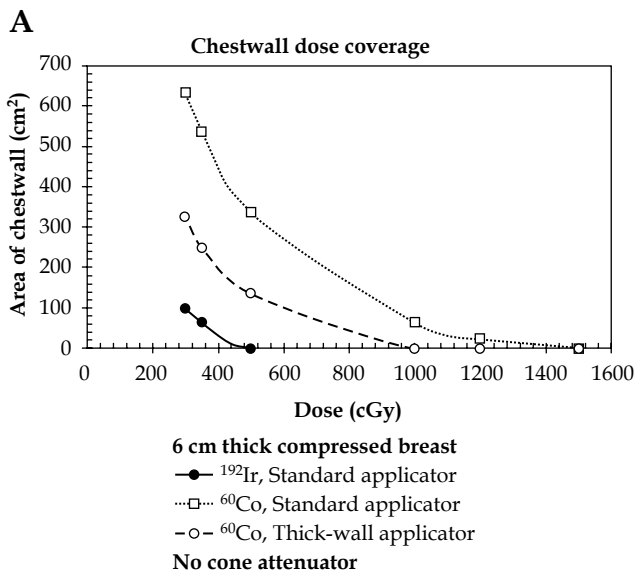


**Fig. 8.** Comparison of the area of the chest wall covered by different dose values, for a 6 cm thick compressed breast, with different source and applicator combinations, without **(A)** and with **(B)** cone attenuator. The calculations are obtained for a 6 cm diameter applicator

**Table 1.** Comparison of areas of the chest wall that were covered by different isodose lines using an HDR $^{60}$Co source with the standard and thick-walled applicator and an HDR $^{192}$Ir source with the standard applicator. The maximum chest wall area that was considered in these calculations (as shown in Figure 5B) was 900 cm$^2$

| Without a conical attenuator | Compressed breast thickness | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Chest wall area (in cm$^2$) covered by: | $^{60}$Co Standard applicator | | | $^{60}$Co Thick applicator | | | $^{192}$Ir Standard applicator | | |
| | 4 cm | 6 cm | 8 cm | 4 cm | 6 cm | 8 cm | 4 cm | 6 cm | 8 cm |
| Doses more than 3.5 Gy | 539.3 | 717.5 | 826.3 | 251.7 | 435.5 | 614.0 | 67.2 | 143.5 | 239.5 |
| Doses more than 5 Gy | 338.0 | 517.0 | 668.0 | 137.0 | 243.0 | 408.2 | 0.3 | 45.7 | 134.0 |
| Doses more than 10 Gy | 64.3 | 158.8 | 277.5 | 0.0 | 26.3 | 99.2 | 0.0 | 0.0 | 0.0 |
| Doses more than 12 Gy | 23.8 | 76.8 | 184.2 | 0.0 | 3.2 | 35.5 | 0.0 | 0.0 | 0.0 |
| Doses more than 15 Gy | 0.0 | 29.5 | 79.3 | 0.0 | 0.0 | 5.04 | 0.0 | 0.0 | 0.0 |
| With a conical attenuator | 4 cm | 6 cm | 8 cm | 4 cm | 6 cm | 8 cm | 4 cm | 6 cm | 8 cm |
| Doses more than 3.5 Gy | 468.3 | 630.5 | 822.8 | 174.0 | 335.5 | 610.0 | 7.5 | 50.2 | 263.2 |
| Doses more than 5 Gy | 268.7 | 427.8 | 665.0 | 71.0 | 162.5 | 400.2 | 0.0 | 4.5 | 150.5 |
| Doses more than 8 Gy | 76.8 | 170.3 | 400.0 | 7.3 | 39.5 | 173.0 | 0.0 | 0.0 | 26.0 |
| Doses more than 10 Gy | 29.5 | 90.3 | 271.3 | 0.0 | 12.0 | 93.3 | 0.0 | 0.0 | 0.0 |
| Doses more than 20 Gy | 0.0 | 0.0 | 2.14 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

chest wall for thick-wall applicator relative to the standard applicator. The influence of the applicator thickness on the chest wall is better shown in Figure 8 and Table 1. This figure shows that for a 6 cm thick compressed breast and 6 cm diameter applicator, the area of the chest wall covered by a given dose by HDR $^{60}$Co source is much smaller with thick-wall applicator than the standard applicator. The differences become smaller for larger doses as these isodose lines are covering the tissues that are located between the two applicators, hence the applicator thickness may not have much effect on them.

The maximum chest wall dose with the thick-wall applicator and HDR $^{60}$Co source is 15 Gy (Figure 8A) as compared to 5 Gy with HDR $^{192}$Ir source and standard applicator. In addition Figure 8B shows the reduction of the chest wall dose using the cone attenuator in the applicator, for both source types. Similar results were obtained for the 4 cm and 8 cm thick compressed breast. As shown in Figure 5B, the maximum chest wall area that was considered in these calculations was 900 cm$^2$. Table 1 shows the tabulated data for the chest wall doses in the three different breast thicknesses, in the presence and absence of the attenuating cone. These results indicate that without the cone attenuator in the applicator for a 6 cm thick breast the 10 Gy isodose covers about 158.8 cm$^2$ and 26.3 cm$^2$ for the HDR $^{60}$Co source with the standard and thick-wall applicator, respectively. Therefore, increasing the applicator wall thickness from 6 mm to 12 mm reduces the area of the chest wall covered by 10 Gy by about a factor of 6. Similar evaluation for results with the cone attenuator indicates a reduction factor of 7.5 for the area of the chest wall covered by 10 Gy, when the wall thickness is changed from 6 mm to 12 mm. A combination of wall thickness and attenuator reduces the skin dose from 158.8 cm$^2$ to 12 cm$^2$ (factor of 13).

Figure 9 and Table 2 show the dose distribution to the breast skin that is calculated in a plane immediately after the compression plates, with and without the attenuating cone. These results are presented in terms of the breast skin area (cm$^2$) as a function of isodose values delivered with HDR $^{192}$Ir and $^{60}$Co sources, using the standard and thick-walled applicators. As shown in Figure 9, increasing the applicator wall thickness from 6 mm to 12 mm reduces the skin dose significantly for doses below 20 Gy. However, the impact of the wall thickness is reduced for larger doses. In addition, for dose greater than 20 Gy, the differences of the skin dose for the two source types are less than 20%. For example, as shown in Table 2, the breast skin areas covered by the 45 Gy isodose lines for the 6 cm thick compressed breast are 23.0 cm$^2$, 24.4 cm$^2$, and 24.6 cm$^2$ for the $^{192}$Ir source in the standard applicator and the $^{60}$Co source in standard and thick applicators, respectively.

## Discussion

Feasibility of HDR $^{60}$Co for the NIBB modality was evaluated in the current study. This evaluation was performed by comparing MC simulated dose distributions for an HDR $^{60}$Co source in several breast geometries with those from the HDR $^{192}$Ir system. Calculations were performed for the standard applicator and breast phantom geometries for both sources, and also with a thick-walled applicator for the HDR $^{60}$Co to reduce the chest wall and skin doses. The simulations were performed for two commercially-available HDR sources; the microSelectron $^{192}$Ir and the BEBIG $^{60}$Co source as examples for these radionuclides. In these simulations, the $^{60}$Co source strength was selected such that the dose to the midpoint of the breast would be identical to that of the $^{192}$Ir source.
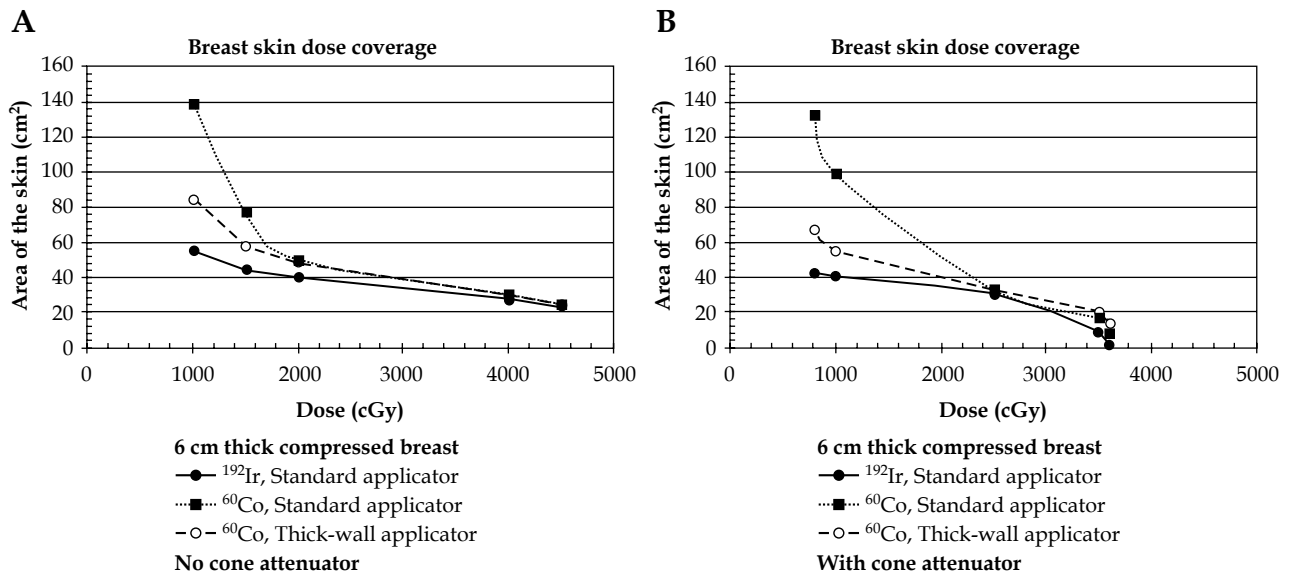
**A**



**B**



**Fig. 9.** Comparison of the area of the skin covered by different dose values, for a 6 cm thick compressed breast, with different source and applicator combinations, without **(A)** and with **(B)** cone attenuator. The calculations are obtained for a 6 cm diameter applicator

**Table 2.** Comparison of areas of the breast skin covered by different isodose lines using an HDR $^{60}$Co source with the standard and thick-walled applicator and an HDR $^{192}$Ir source with the standard applicator

| Without a conical attenuator | Compressed breast thickness | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Skin area (in cm$^2$) covered by: | $^{60}$Co Standard applicator | | | $^{60}$Co Thick applicator | | | $^{192}$Ir Standard applicator | | |
| | 4 cm | 6 cm | 8 cm | 4 cm | 6 cm | 8 cm | 4 cm | 6 cm | 8 cm |
| More than 10 Gy | 120.3 | 139.2 | 144.0 | 68.2 | 85.2 | 115.0 | 50.9 | 55.5 | 60.1 |
| More than 15 Gy | 55.5 | 77.6 | 122.1 | 50.9 | 58.1 | 67.5 | 40.8 | 44.5 | 50.2 |
| More than 20 Gy | 40.8 | 49.8 | 65.0 | 40.8 | 48.6 | 55.1 | 33.4 | 40.6 | 42.6 |
| More than 40 Gy | 9.9 | 30.2 | 33.4 | 7.8 | 30.2 | 33.4 | 8.8 | 27.9 | 31.6 |
| More than 45 Gy | 0.0 | 24.4 | 31.6 | 0.0 | 24.6 | 31.6 | 0.0 | 23.0 | 31.6 |
| With a conical attenuator | 4 cm | 6 cm | 8 cm | 4 cm | 6 cm | 8 cm | 4 cm | 6 cm | 8 cm |
| More than 8 Gy | 99.1 | 132.9 | 143.8 | 55.8 | 67.7 | 104.4 | 40.8 | 42.8 | 44.2 |
| More than 10 Gy | 52.8 | 99.1 | 135.2 | 49.3 | 55.5 | 66.1 | 37.1 | 40.8 | 40.8 |
| More than 25 Gy | 29.5 | 33.2 | 36.4 | 29.3 | 33.2 | 36.9 | 25.3 | 30.4 | 31.3 |
| More than 35 Gy | 0.0 | 17.0 | 30.4 | 0.0 | 20.5 | 30.2 | 0.0 | 9.2 | 27.2 |
| More than 36 Gy | 0.0 | 8.1 | 29.7 | 0.0 | 14.0 | 29.7 | 0.0 | 1.6 | 26.0 |

The results of these investigations show that the dose distributions within the treatment volume are nearly identical for HDR $^{192}$Ir and $^{60}$Co sources. In short, the AccuBoost paradigm for using HDR $^{192}$Ir to deliver uniform central dose distributions and low skin doses held true HDR $^{60}$Co using thick-walled applicators. These results are consistent with the reported data by Andrássy *et al.*, which indicated that both radionuclides deliver similar dose distributions within the treatment volume [35]. Thus,

the existing optimizations and inverse planning tools provide similar results. Moreover, Richter *et al.* reported a comparison of the TG-43 dosimetry characteristics of the HDR $^{192}$Ir and $^{60}$Co sources [11], and concluded that there are no advantages or disadvantages in clinical aspects for HDR $^{60}$Co sources in comparison to HDR $^{192}$Ir sources. In a similar evaluation, Bahreyni-Toossi *et al.* found that the value of dose rate constant for the GZP6 and Ralstron type HDR $^{60}$Co sources were similar to that for the mi-

croSelectron $^{192}$Ir source [4]. Furthermore, they noted that the other TG-43 dosimetry parameters for the GZP6 and Ralstron HDR $^{60}$Co sources were similar. Breast cosmesis has been shown to the whole-breast integral dose [23, 24, 25]. Based on the results of Islam et al [31], the integral dose for HDR breast brachytherapy may be lower for $^{60}$Co than for $^{192}$Ir.

Using the dosimetric parameters of the sources, it could be demonstrated that for a 6 cm thick breast, treated with 6 cm diameter applicators, the treatment time for delivery of 3.4 Gy per fraction may be ranging approximately from 20 minutes to 40 minutes for 10 Ci to 5 Ci $^{192}$Ir source, respectively. However, the treatment times may change to 30 minutes to 60 minutes for the presently available model 2.0 Ci to 1.0 Ci $^{60}$Co BEBIG source.

The results of these investigations have demonstrated that the impact of the applicator thickness was noticeable for the reduction of the skin doses below 20 Gy (Table 2 and Figure 9). However, for doses larger than 20 Gy, the thickness of the applicator does not have much effect on the skin dose. For example, for a 6 cm thick compressed breast, in absence of the attenuating cone, the skin area covered by the 15 Gy isodose line with the $^{60}$Co source with standard and thick-walled applicators were 77.6 cm$^2$ and 58.1 cm$^2$, respectively. This is a reduction of about 25%. The differences between the $^{60}$Co source with the thick applicator and $^{192}$Ir source with the standard applicator were decreased to within 10% at the 45 Gy isodose lines. Similar results were observed for different breast thicknesses. It should be noted that the skin doses presented herein were only for a two opposing fields. However, in an actual treatment, a 4-field technique or two sets of orthogonally oriented applicators would be used, which leads to a lower skin dose [38].

Moreover, the influence of the applicator thickness on the chest wall dose was demonstrated in Table 1 and Figure 8. These results show that, without the cone attenuator, the maximum chest wall dose with the thick-wall applicator and HDR $^{60}$Co source is 10 Gy (Figure 8A). This will reduce to 8 Gy with the use of cone attenuator.

Finally, the impact of a conical attenuator within the applicator on the dose distribution of different breast thicknesses for $^{60}$Co was shown to be similar to that for the $^{192}$Ir source. In addition, reductions of the chest wall and breast skin doses for $^{60}$Co were similar as observed for the $^{192}$Ir source.

## Conclusions

In conclusion, HDR $^{60}$Co brachytherapy appears to be a good alternative radionuclide to HDR $^{192}$Ir brachytherapy as used for APBI treatments of breast cancer using the AccuBoost technique. In these treatments, the accumulated dose from 10 fractions in 5 days to the center of the breast would be 3400 cGy for each source type. Moreover, the actual treatments should be delivered in 10 fractions, as it is customary for $^{192}$Ir source. The mechanism for applicator usage and clinical placement for irradiation with $^{60}$Co should be similar to the currently used systems with $^{192}$Ir sources [38]. It should be emphasized that the impact

of the applicator weight and thickness on the assembly system of the treatment unit were beyond the scope of the current project. In the next step of this project, these issues will be evaluated prior to the clinical application of this system. Further, the elongated treatment time for the presently available $^{60}$Co source models will also be evaluated.

## Disclosure

Authors report no conflict of interest.

## References

1. Mesbahi A, Naseri A. In-air calibration of new high dose rate $^{60}$Co brachytherapy sources: results of measurements on a GZP6 brachytherapy afterloading unit. *Rep Pract Oncol Radiother* 2008; 13: 69-73.
2. Bahreyni-Toossi MT, Ghorbani M, Mowlavi AA et al. Air kerma strength characterization of a GZP6 Cobalt-60 brachytherapy source. *Rep Pract Oncol Radiother* 2010; 15: 190-194.
3. Bahreyni-Toossi MT, Abdollahi M, Ghorbani M. Monte Carlo dose calculation of GZP6 $^{60}$Co stepping source based on a matrix shift technique. *Rep Pract Oncol Radiother* 2010; 16: 10-13.
4. Bahreyni-Toossi MT, Ghorbani M, Mowlavi AA et al. Dosimetric characterizations of GZP6 $^{60}$Co high dose rate brachytherapy sources: application of superimposition method. *Radiol Oncol* 2012; 46: 170-178.
5. Tabrizi SH, Kamali Asl A, Azma Z. Monte Carlo derivation of AAPM TG-43 dosimetric parameters for GZP6 Co-60 HDR sources. *Physica Medica* 2012; 28: 153-160.
6. Papagiannis P, Angelopoulos A, Pantelis E et al. Monte Carlo dosimetry of $^{60}$Co HDR brachytherapy sources. *Med Phys* 2003; 30: 712-721.
7. Ballester F, Granero D, Perez-Calatayud J et al. Monte Carlo dosimetric study of the BEBIG Co-60 HDR source. *Phys Med Biol* 2005; 50: 309-316.
8. Granero D, Pérez-Calatayud J, Ballester F. Technical note: Dosimetric study of a new Co-60 source used in brachytherapy. *Med Phys* 2007; 34: 3485-3488.
9. Tolli H, Johansson KA. Absorbed dose determination at short distance from $^{60}$Co and $^{192}$Ir brachytherapy sources. *Phys Med Biol* 1998; 43: 3183-3194.
10. Sahoo S, Palani Selvam T, Vishwakarma RS et al. Monte Carlo modeling of $^{60}$Co HDR brachytherapy source in water and in different solid water phantom materials. *J Med Phys* 2010; 35: 15-22.
11. Richter J, Baier K, Flentje M. Comparison of $^{60}$Cobalt and $^{192}$Iridium sources in high dose rate afterloading brachytherapy. *Strahlenther Onkol* 2008; 4: 187-192.
12. Strohmaier S, Zwierzchowski G. Comparison of $^{60}$Co and $^{192}$Ir sources in HDR brachytherapy. *J Contemp Brachytherapy* 2011; 3: 199-208.
13. Ntekim A, Adenipekun A, Akinlade B et al. High dose rate brachytherapy in the treatment of cervical cancer: preliminary experience with cobalt 60 radionuclide source – a prospective study. *Clin Med Insights Oncol* 2010; 4: 89-94.
14. Palmer A, Hayman O, Muscat S. Treatment planning study of the 3D dosimetric differences between Co-60 and Ir-192 sources in high dose rate (HDR) brachytherapy for cervix cancer. *J Contemp Brachytherapy* 2012; 4: 52-59.
15. Azhari HA, Hensley F, Schütte W et al. Dosimetric verification of source strength for HDR afterloading units with Ir-192 and Co-60 photon sources: Comparison of three different international protocols. *J Med Phys* 2012; 37: 183-192.

16. Nath R, Anderson LL, Luxton G et al. Dosimetry of interstitial brachytherapy sources: Recommendations of the AAPM Radiation Therapy Committee Task Group No. 43. *Med Phys* 1995; 22: 209-234.

17. Rivard MJ, Coursey BM, DeWerd LA et al. Update of AAPM Task Group No. 43 Report: A revised AAPM protocol for brachytherapy dose calculations. *Med Phys* 2004; 31: 633-674.

18. Perez-Calatayud J, Ballestera F, Das RK et al. Dose calculation for photon-emitting brachytherapy sources with average energy higher than 50 keV: Report of the AAPM and ESTRO. *Med Phys* 2012; 39: 2904-2929.

19. AccuBoost for image guided breast irradiation, Advanced Radiation Therapy, Tyngsboro, MA 01879. http://www.accuboost.com/ last accessed 23 November 2015.

20. Rivard MJ, Melhus CS, Wazer DE et al. Dosimetric characterization of round HDR $^{192}$Ir AccuBoost applicators for breast brachytherapy. *Med Phys* 2009; 36: 5027-5032.

21. Iftimia I, Talmadge M, Ladd R, Halvorsen P. Commissioning and quality assurance for the treatment delivery components of the AccuBoost system. *Applied Clin Med Phys* 2015; 16: 129-143.

22. Sioshansi S, Rivard MJ, Hiatt JR et al. Dose modeling of noninvasive image-guided breast brachytherapy in comparison to electron beam boost and three-dimensional conformal accelerated partial breast irradiation. *Int J Radiat Oncol Biol Phys* 2011; 80: 410-416.

23. Hepel JT, Wazer DE. A comparison of brachytherapy techniques for partial breast irradiation. *Brachytherapy* 2012; 11: 163-175.

24. Patel RR, Das RK. Review of Image-guided breast brachytherapy: an alternative to whole-breast radiotherapy. *Lancet Oncol* 2006; 7: 407-415.

25. Hepel JT, Hiatt JR, Sha S et al. The rationale, technique, and feasibility of partial breast irradiation using noninvasive image-guided breast brachytherapy. *Brachytherapy* 2014; 13: 493-501.

26. Kuo HC, Mehta KJ, Hong L et al. Day to day treatment variations of accelerated partial breast brachytherapy using a multi-lumen balloon. *J Contemp Brachytherapy* 2014; 6: 68-75.

27. Koh VY, Buhari SA, Tan PW et al. Comparing a volume based template approach and ultrasound guided freehand approach in multicatheter interstitial accelerated partial breast irradiation. *J Contemp Brachytherapy* 2014; 6: 173-177.

28. Gutiérrez C, Najjari D, Martínez E et al. The use of an interstitial boost in the conservative treatment of breast cancer: How to perform it routinely in a radiotherapy department. *J Contemp Brachytherapy* 2015; 6: 397-403.

29. Paryani NN, Vallow L, Magalhaes W. The incidence of fat necrosis in balloon-based breast brachytherapy. *J Contemp Brachytherapy* 2015; 7: 29-34.

30. Chesta MÁ, Puma AL, McDonnell DJ. Kerma and photons absorbed-dose from Ir-192 HDR seeds. *European J Biophys* 2014; 2: 72-80.

31. Islam MA, Akramuzzaman M, Zakaria GA. Dosimetric comparison between the microSelectron HDR $^{192}$Ir v2 source and the BEBIG $^{60}$Co source for HDR brachytherapy using the EGSnrc Monte Carlo transport code. *J Med Phys* 2012; 37: 219-225.

32. Andrássy M, Niatsetsky Y, Pérez-Calatayud J. Co-60 versus Ir-192 in HDR brachytherapy: Scientific and technological comparison. *Rev Fis Med* 2012; 13: 125-130.

33. MCNP-5 Monte Carlo Team. MCNP – A general Monte Carlo N-Particle transport code, version 5. Los Alamos National Laboratory, Los Alamos, NM. 2003.

34. Briesmeister JF. MCNP – A general Monte Carlo N particle transport code. Version 4C. Los Alamos National Laboratory Report LA-12625. 2000.

35. Zehtabian M, Sina S, Faghihi R et al. Perturbation of TG-43 parameters of the brachytherapy sources under insufficient scattering materials. *J Appl Clin Med Phys* 2013; 14: 164-176.

36. Sina S, Faghihi R, Meigooni AS et al. Simulation of the shielding effects of an applicator on the AAPM TG-43 parameters of Cs-137 Selectron LDR brachytherapy sources. *Iran J Radiat Res* 2009; 7: 135-140.

37. Safigholi H, Sardari D, Karimi Jashni S et al. An analytical model to determine interseed attenuation effect in low-dose-rate brachytherapy. *J Appl Clin Med Phys* 2013; 14: 150-163.

38. Rivard MJ, Ghadyani HR, Bastien AD et al. Multi-axis dose accumulation of noninvasive image-guided breast brachytherapy through biomechanical modeling of tissue deformation using the finite element method. *J Contemp Brachytherapy* 2015; 7: 55-71.