Available online at www.sciencedirect.com

ScienceDirect

journal homepage: http://www.elsevier.com/locate/rpor

Original research article

Study of the dosimetric differences between ^{192}Ir and ^{60}Co sources of high dose rate brachytherapy for breast interstitial implant

Mourougan Sinnatamby[a,*], *Vivekanandan Nagarajan*[b], *Reddy Kanipakam Sathyanarayana*[a,c], *Gunaseelan Karunanidhi*[a], *Vivekanandam Singhavajala*[a]

[a] *Department of Radiotherapy, Regional Cancer Centre, JIPMER, Puducherry, India*
[b] *Department of Medical Physics, Cancer Institute, Adyar, Chennai, India*
[c] *Department of Oncology, Mahatma Gandhi Medical College and Research Institute, Puducherry, India*

ARTICLE INFO

Article history:
Received 16 June 2015
Received in revised form
27 January 2016
Accepted 15 March 2016
Available online 11 May 2016

Keywords:
^{60}Co
^{192}Ir
HDR
Breast
Interstitial implant

ABSTRACT

Aim: The study intends to compare ^{192}Ir source against the ^{60}Co source for interstitial breast metal implant in high dose rate brachytherapy.

Background: Few studies have been reported to compare ^{60}Co and ^{192}Ir on HDR brachytherapy in gynaecology and prostate cancer and very few with reference to breast cancer.

Materials and methods: Twenty patients who had undergone interstitial template guided breast implant were treated in HDR ^{192}Ir brachytherapy unit. Plans were generated substituting ^{60}Co source without changing the dwell positions and optimization. Cumulative dose volume histograms were compared.

Results: The reference isodose line enclosing CTV (CTV_{ref}) and the 2.34% difference seen in the volume enclosed by the reference isodose line (V_{ref}) between the two isotopes show small but statistically significant difference ($p < 0.05$). In DHI, no difference was observed in the relative dose between the two sources ($p = 0.823$). The over dose volume index showed 11% difference. The conformity index showed 2.32% difference compared to ^{192}Ir ($p < 0.05$).

D_{mean} (%) and D_{max} (%) for the heart, ipsilateral lung, ipsilateral ribs, skin presented very small difference. $V_{5\%}$ and $V_{10\%}$ of the heart shows 25% and 32% difference in dose. D_{2cc} (%) and $D_{0.1cc}$ (%) for the contralateral breast, contralateral lung and D_{2cc} (%) of the skin displayed significant difference ($p < 0.05$). However, $D_{0.1cc}$ (%) of the skin indicated no noteworthy difference with $p = 0.343$.

Conclusion: Based on the 3D dosimetric analysis of patient plans considered in this study, most of the DVH parameters showed statistically significant differences which can be

* *Corresponding author at*: Department of Radiotherapy, Regional Cancer Centre, Jawaharlal Institute of Postgraduate Medical Education and Research, Puducherry 605 006, India. Tel.: +91 94423 38389.
E-mail addresses: mourougans@gmail.com, mourougan.s@jipmer.edu.in (M. Sinnatamby).
http://dx.doi.org/10.1016/j.rpor.2016.03.005

reduced by treatment planning optimization techniques. ^{60}Co isotope can be used as a viable alternative because of its long half-life, logistic advantages in procurement, infrequent need of source replacement and disposal of used source.

1. Background

Interstitial brachytherapy in breast cancer offers a conformal dose delivery with the ability to reduce the dose to the lung, heart, skin and ribs. Satisfactory results of local control and positive cosmetic outcome have been documented. In clinical practice, it was understood that deeply seated target volumes can be covered more accurately by interstitial implants than by electron beams.[1] Radiotherapy centres worldwide have started using ^{60}Co sources in a modern high dose-rate (HDR) brachytherapy treatment units to verify dosimetric data and to put them into clinical use. These new systems utilize miniaturized ^{60}Co sources, rather than traditional ^{192}Ir sources and are becoming popular due to longer source replacement intervals, lower operating costs and a reduced frequency of movement of radioactive sources between countries, compared to ^{192}Ir.[2] While the availability of miniaturized high specific activity ^{60}Co sources for high dose-rate brachytherapy is a recent development, the use of physically larger ^{60}Co sources in low dose-rate applications have a long history dating back to the 1960s and 1970s with the Cathetron, Ralstron and Selectron treatment units reported in 1964 by Henschke.[3]

Typical HDR remote after loading units use ^{192}Ir source with a nominal source strength of about 370 GBq (10 Ci) changed at a frequency of three months. An alternative HDR remote after loader (Multisource; Eckert & Ziegler BEBIG GmbH, Berlin, Germany) offers similar functionality; however, the isotope can be ^{60}Co with a nominal initial activity of 74 GBq (2 Ci) and the frequency for source change is proposed to be five years.[4]

Recently, ^{60}Co sources have became available with identical geometrical dimensions as miniaturized ^{192}Ir sources. The smaller size of the source allowed interstitial treatment and optimization of dose.[5] The dosimetric data sets provided by Granero et al.[6] are used as input to validate treatment planning system calculation using ^{60}Co. The dose deposition differences around single ^{60}Co and ^{192}Ir sources (anisotropy, radial dose function and relative isodose curves) have been reviewed by Strohmaier[5] who found no advantage or disadvantage for ^{60}Co sources compared to ^{192}Ir. However, this review is based on the available work by Venselaar,[7] Richter et al.[8] and Park et al.,[9] who confined their analysis to point dose and qualitative isodose comparisons.

The difference in the photon spectrum between ^{60}Co (higher mean energy 1.25 MeV) and ^{192}Ir (0.355 MeV) has to be considered with respect to dose distribution in water. Contributors of dose deposition in water are the photoelectric and Compton effects. However, in clinical situation there are no differences, because the inverse square law is clearly the most dominant physical effect in brachytherapy. The comparison of the anisotropy functions reveals less absorption in source core and capsule for ^{60}Co. The consequences of ^{60}Co radiation in absorption and scattering effects are, in comparison to ^{192}Ir, attenuation effects in applicators or contrast agents being reduced. Moreover, the effect of that over-estimation by TG-43 when approaching the surfaces water-to-air is lower for ^{60}Co than for ^{192}Ir. In relevant cases, one should therefore expect less deviation in treatment planning with the software working on TG-43.[10]

2. Aim

The study intends to compare ^{192}Ir source against the ^{60}Co source for interstitial breast metal implant in high dose rate brachytherapy.

3. Materials and methods

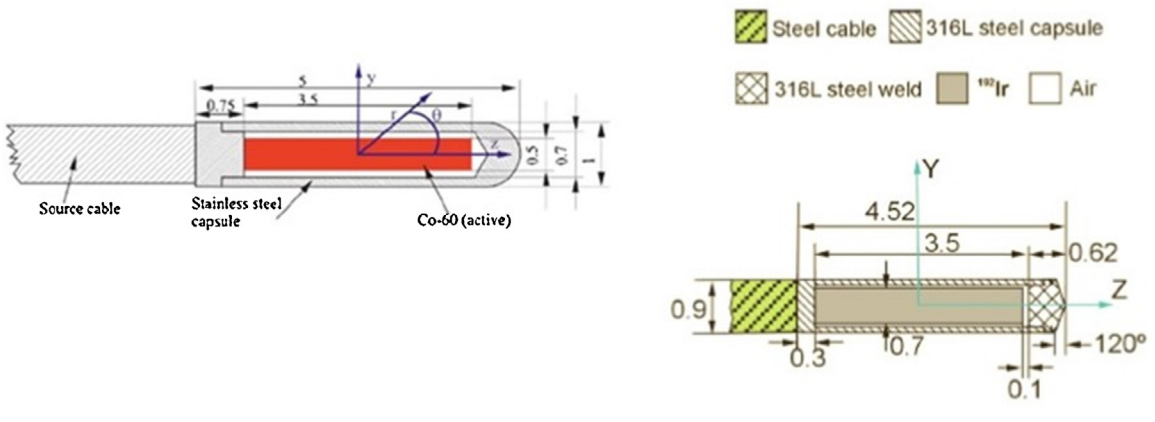
This study includes 20 patients who were considered for breast conservative surgery (BCS). They underwent lumpectomy and axillary dissection. Initially, patients received preoperative interstitial high dose rate brachytherapy as upfront boost using rigid metal implant followed by whole breast irradiation. The inter-plane separation and inter-catheter separation was maintained at 1 cm using a customized template. A 3 mm slice thickness was used to get 3D image data set using a computed tomography simulator. The clinical target volume (CTV) was drawn using surgical clips placed at the time of lumpectomy in the medial, lateral, cranial, caudal, superficial and deep margins. The delineated contours include the contralateral breast, heart, ipsilateral lung, contralateral lung, ribs and skin. The treatment planning system (TPS) used was Brachy Vision version 10.0 software (Varian Medical Systems, Palo Alto, CA). The ^{192}Ir Gammamed HDR plus source listed in the source library was used. Bebig ^{60}Co source was modelled using the data input from Granero et al.[6] The different parameters between ^{192}Ir and ^{60}Co are listed in Table 1.

3.1. *Source design and material*

The ^{60}Co source model Co0.A86 (Multisource; Eckert & Ziegler BEBIG GmbH, Berlin, Germany) and ^{192}Ir Gammmed plus HDR

Table 1 – Comparison of source parameters.

	^{192}Ir	^{60}Co
Half life (months)	2.4	63.3
Initial source strength (GBq)	370	74
Dose rate constant (cGy/hU)	108	306
Air kerma rate constant (mGy/h)	1.108	1.084
$E_{max,\beta}$ (MeV)	0.675	0.318
$\bar{E}_\beta$ (MeV)	0.181	0.096
E_β (MeV)	0.136–1.062	1.17–1.13
$\bar{E}_\gamma$ (MeV)	0.375	1.25



A : Schematic view of the 60Co source mod Co0.A86 Dimensions are in millimetres.

B : Schematic view of the 192Ir source mod Gammamed plus iX. Dimensions are in millimetres

Fig. 1 – (A) ^{60}Co source model Co0.A86 (Courtsey: Eckert & Ziegler BEBIG GmbH, Berlin, Germany). (B) ^{192}Ir source model Gammamed plus iX.
Courtsey: Gammamed plus iX, Varian Medical Systems, Palo Alto, CA.

source model (Gammamed plus iX, Varian Medical Systems, Palo Alto, CA) are shown in Fig. 1.

3.2. *Monte Carlo simulations*

In this study, a complete dosimetric data set for the new BEBIG 60Co source model Co0.A86 was obtained for an unbounded liquid water phantom using the Monte Carlo GEANT4 code. The dosimetric data sets given in this study were used as input and to validate the TPS calculations.

3.3. *Treatment planning*

Initially, the 3D dose was calculated using ^{192}Ir Gammamed plus source and optimization was done using either geometrical or graphical. Inverse planning was also done in some cases. Using the approved plan, study was carried out using Bebig ^{60}Co (Co0.A86) without changing the dwell positions and optimization. Total dose planned was 15 Gy in six fractions, two fractions daily with a gap of 6 h between them. All plans were compared using the cumulative dose volume histogram.

3.4. *Dosimetric parameters*

All contours were delineated as shown in Fig. 2. The dose coverage of the clinical target volume was evaluated. The reference isodose enclosing the clinical target volume (CTV_{ref}), reference isodose covering the volume (V_{ref}), which might include volume other than the target volume, volume enclosing 150% isodose and volume enclosing 200% isodose line were all estimated and compared.

The indices used in this study[11–13] are as follows:

$$\text{Coverage index (CI)}: \quad \frac{\text{CTV reference}}{\text{CTV volume ideal}} (\text{ideal CI} = 1).$$

$$\text{Dose homogeneity index (DHI)}: \quad 1 - \frac{V_{150\%}}{CTV_{ref}} (\text{ideal DHI} = 1).$$

$$\text{Overdose volume index (OI)}: \quad \frac{V_{200\%}}{\text{CTV reference}} (\text{ideal OI} = 0).$$

$$\text{External volume index (EI)}: \quad 1 - \frac{\text{CTV reference}}{V_{ref}} (\text{ideal EI} = 0).$$

$$\text{Conformity index (COIN)}: \quad C_1 \times C_2,$$

where $C_1 = CTV_{ref}/\text{CTV volume}$ and $C_2 = CTV_{ref}/V_{ref}$ (ideal COIN = 1).

COIN describes how well the reference dose encompasses the CTV and excludes nontarget structures. Since organs at risk are as important as CTV, dose to these organs or tissue at risk need to be studied. D_{mean} and D_{max} received by organs such as the heart, skin and ribs on the affected side, ipsilateral lung and ipsilateral breast excluding CTV were all estimated. Volume parameters, like $V_{5\%}$, $V_{10\%}$ for the heart and ipsilateral lung, D_{2cc}, $D_{0.1cc}$ of the heart, lung, skin, ribs on the affected side and contralateral breast and lung were included.

4. Results

Results of evaluated parameters are presented in Table 2. Statistical analysis was done using SPSS 21 software. The

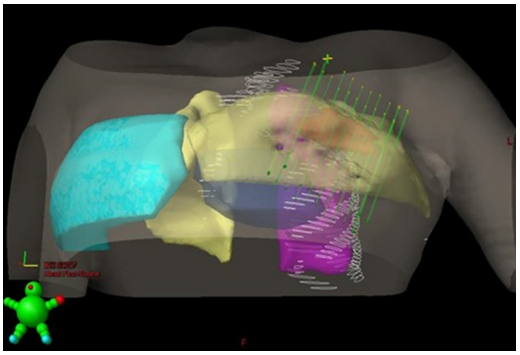


Fig. 2 – 3D images of treated target volume and other OAR's.

Table 2 – Physical factors appraised in the treatment plan.

	^{60}Co TG-43			^{192}Ir TG-43			% Diff	Wilcoxon signed rank test	p-Value	Significance
	Mean ± SD	Median	Range	Mean ± SD	Median	Range				
CTV (cc)	55.58 ± 26.19	49.95	24.8–102.2	55.58 ± 26.19	49.95	24.8–102.2	–	–	–	–
CTVref (cc)	50.89 ± 24.53	44.38	21.83–117.24	51.96 ± 25.33	45.3	21.97–120.33	2.06	3.808	<0.05	S
V_{ref} (cc)	54.6 ± 25.07	48.05	23.7–120.4	55.91 ± 25.87	49.4	23.9–123.4	2.34	3.924	<0.05	S
$V_{150\%}$ (cc)	18.7 ± 12.13	16	8.2–56.7	19.19 ± 12.51	16.55	5.6–58	2.55	3.225	<0.05	S
$V_{200\%}$ (cc)	5.02 ± 3.93	3.55	0.7–16.1	4.96 ± 3.96	3.4	0.7–16.2	1.21	2.138	<0.05	S
Coverage index (CI)	0.91 ± 0.03	0.9	0.84–0.95	0.93 ± 0.03	0.94	0.84–0.97	2.15	3.845	<0.05	S
Overdose volume index (OI)	0.1 ± 0.05	0.09	0.02–0.26	0.09 ± 0.05	0.08	0.02–0.25	11.11	3.92	<0.05	S
External volume index (EI)	0.07 ± 0.04	0.07	0.02–0.17	0.08 ± 0.04	0.07	0.02–0.18	12.5	1.195	0.232	NS
Conformity index (COIN)	0.84 ± 0.04	0.9	0.7–0.9	0.86 ± 0.05	0.87	0.7–0.93	2.36	3.173	<0.05	S

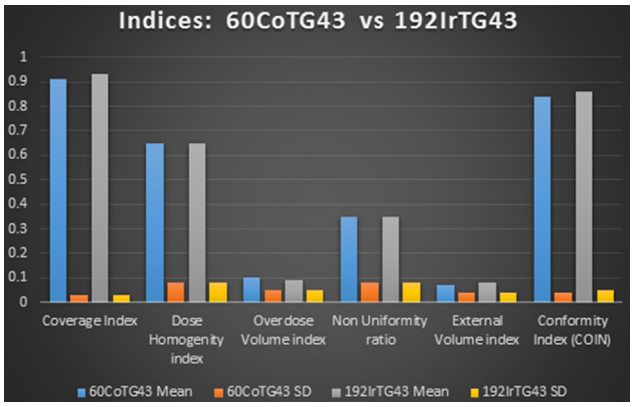


Fig. 3 – Comparison of indices between ^{60}Co TG-43 versus ^{192}Ir TG-43.

reference isodose line enclosing CTV for both sources shows small, but statistically significant difference. The 2.34% difference seen in the volume enclosed by the reference isodose line between the two isotopes ($p < 0.05$). $V_{150\%}$ and $V_{200\%}$ comparison displays 2.5% and 1.2% difference, respectively, with statistical significant result. The comparisons of various indices used in this study are highlighted in the histogram as shown in Fig. 3. In both Dose Homogeneity Index (DHI) and Dose Non-uniformity Ratio, no difference was found in the relative dose between two sources. The overdose volume index showed 11% difference. The EI was 12.5% higher than ^{192}Ir. The coverage index and the conformity index was 2.15% and 2.32% lower compared to ^{192}Ir and proved to be a statistically significant result with $p \leq 0.05$. The cumulated DVH is shown in Fig. 4. The ipsilateral breast excluding the CTV volume was also evaluated and compared. The D_{mean} value and V25% volume showed statistically significant difference.

D_{mean} (%) and D_{max} (%) for the heart, ipsilateral lung, ipsilateral ribs, skin are shown in Table 3 with statistically significant difference ($p \leq 0.05$). $V_{5\%}$ and $V_{10\%}$ of the heart shows 25% and 32% difference in dose. From Table 4, D_{2cc} (%) and $D_{0.1cc}$ (%) for the contralateral breast, contralateral lung and D_{2cc} (%) of the skin displayed a statistically significant difference ($p \leq 0.05$). However, $D_{0.1cc}$ (%) of the skin indicated no noteworthy difference with $p = 0.343$.

The dose prescription and fractionation scheme remain the same in both plans. The dwell positions were not altered as the plan was compared between relative dose distributions while using two sources, the dwell time will change based on the energy spectrum between two sources. The average treatment time to deliver doses to CTV was 1.798 times longer when ^{60}Co source was used.

5. Discussion

In the clinical practice of brachytherapy in breast cancer, ^{192}Ir has been used traditionally because of its finite size and high specific activity. The new HDR after loaders using ^{60}Co have also provided the same finite size with reasonable high specific activity for clinical use. However, because of higher energy of

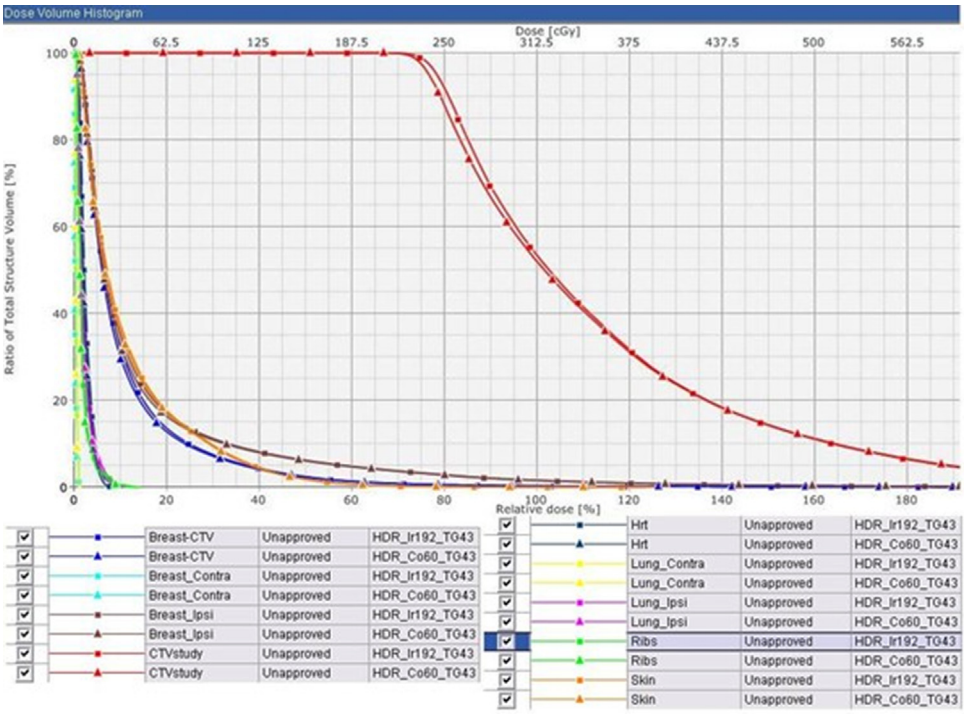


Fig. 4 – Cumulated dose volume histogram.

Table 3 – D_{mean} and D_{max} values comparison between ^{60}Co and ^{192}Ir of heart, ipsilateral lung, ribs and skin.

	Parameters	^{60}Co TG-43 Mean ± SD	^{192}Ir TG-43 Mean ± SD	% Diff	Wilcoxon signed rank test	*p*-Value	Significance
Heart	D_{mean} (%)	2.24 ± 1.02	2.58 ± 1.14	13.18	3.945	<0.05	S
	D_{max} (%)	8.55 ± 5.53	9.37 ± 5.95	8.75	3.925	<0.05	S
Ipsilateral lung	D_{mean} (%)	2.59 ± 0.77	2.91 ± 0.88	10.99	3.857	<0.05	S
	D_{max} (%)	15.18 ± 5.85	16.44 ± 6.18	7.66	3.926	<0.05	S
Ipsilateral ribs	D_{mean} (%)	3.59 ± 1.43	3.92 ± 1.59	8.42	3.802	<0.05	S
	D_{max} (%)	18.79 ± 8.65	20.05 ± 9.03	6.28	3.83	<0.05	S
Skin	D_{mean} (%)	11.34 ± 3.84	11.90 ± 4.03	4.71	3.936	<0.05	S
	D_{max} (%)	94.28 ± 28.02	92.39 ± 27.98	2.05	3.099	<0.05	S

Table 4 – D_{2cc} and $D_{0.1cc}$ comparison between ^{60}Co and ^{192}Ir of heart, contralateral breast, lung, ipsilateral lung, ribs and skin.

	Parameters	^{60}Co TG-43 Mean ± SD	^{192}Ir TG-43 Mean ± SD	% Diff	Wilcoxon signed rank test	*p*-Value	Significance
Contralateral breast	$D_{0.1cc}$ (%)	2.49 ± 1.78	2.74 ± 1.94	9.12	3.92	<0.05	S
	D_{2cc} (%)	2.15 ± 1.41	2.37 ± 1.54	9.28	3.92	<0.05	S
Heart	$D_{0.1cc}$ (%)	8.03 ± 5.03	8.82 ± 5.37	8.96	3.922	<0.05	S
	D_{2cc} (%)	6.95 ± 4.06	7.71 ± 4.4	9.86	3.92	<0.05	S
Contralateral lung	$D_{0.1cc}$ (%)	1.76 ± 0.97	1.95 ± 1.07	9.74	3.727	<0.05	S
	D_{2cc} (%)	1.52 ± 0.73	1.73 ± 0.87	12.14	3.826	<0.05	S
Ipsilateral lung	$D_{0.1cc}$ (%)	14.21 ± 5.35	15.44 ± 5.65	7.97	3.921	<0.05	S
	D_{2cc} (%)	12.03 ± 4.21	13.12 ± 4.54	8.31	3.922	<0.05	S
Ribs	$D_{0.1cc}$ (%)	17.02 ± 6.77	18.41 ± 7.12	7.55	3.921	<0.05	S
	D_{2cc} (%)	11.63 ± 4.48	12.64 ± 4.75	7.99	3.922	<0.05	S
Skin	$D_{0.1cc}$ (%)	66.58 ± 11.10	66.84 ± 11.44	0.38	0.948	0.343	NS
	D_{2cc} (%)	51.20 ± 9.66	52.03 ± 10.06	1.59	3.583	<0.05	S

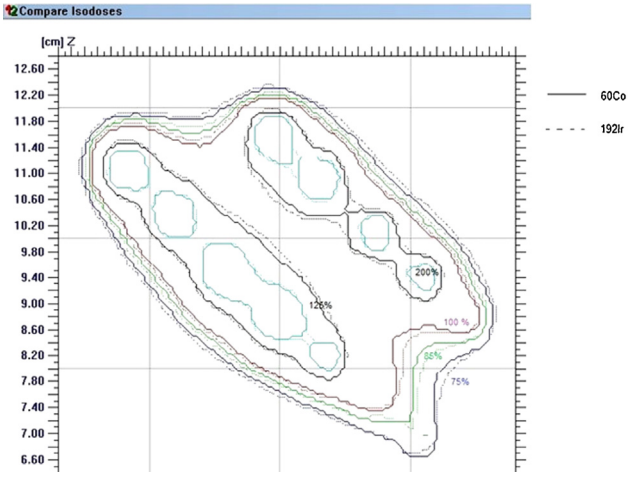


Fig. 5 – Relative isodose curve comparison of plan between ^{60}Co and ^{192}Ir.

^{60}Co, the treatment unit requires a heavier source safe. The HVL of lead is four times larger for ^{60}Co: 12 mm compared to 3 mm for ^{192}Ir. HVL (Half Value Layer) and TVL (Tenth Value Layer) values are used to describe the shielding capacity of a certain material.

Similarly, the treatment room designed for ^{192}Ir after loader is not suitable for ^{60}Co after loader and needs additional shielding.[14] With a total number of 20 breast brachytherapy applications, there are no substantial differences between the two isotopes with respect to dose prescribing and treatment planning as demonstrated in this study.

No major difference was observed in relative isodose distributions from ^{60}Co and ^{192}Ir as a result of differences in physical properties of the two sources. Similar was the observation in gynaecologic cancer as reported by Palmer et al.[15] The analysis of treatment plans, using a 3D image-based approach, showed only small differences in dose distribution (Fig. 5).

The difference in mean gamma ray energy between ^{60}Co and ^{192}Ir is not significant when dose distribution is calculated according to AAPM TG-43 formalism in terms of dose to water in water.[16] This was demonstrated for a single source and for a typical gynaecologic applicator by Strohmaier et al.[5]

Candela et al.[17] studied organ doses on a reference male phantom for a typical HDR implant of the prostate. For the nearest organs considered doses delivered by ^{60}Co were smaller (8–19%) than for ^{192}Ir. Venselaar et al.[7] estimated the dose value at different distances from ^{60}Co and ^{192}Ir brachytherapy sources, up to 20 cm dose values from ^{192}Ir are slightly higher (1.05–1.14). In this study, doses to organs at risk, like the heart, lung, skin, ribs were marginally lower (0.4–30%) with ^{60}Co as compared to ^{192}Ir as all these are within 20 cm from the implant. Venselaar et al.[7] mentioned the dose value at a distance further than 25 cm are marginally higher than ^{192}Ir, we did not consider this a major disadvantage because of logistical and financial benefits of ^{60}Co. The higher integral dose to the distant organs/body may not cause any immediate concern, but one has to keep in mind the late consequences.

6. Conclusion

The dose distributions for ^{60}Co in interstitial implant of the breast are nearly identical to that of ^{192}Ir. Although all DVH parameters showed statistically significant differences, no advantage or disadvantage exists for ^{60}Co source compared to ^{192}Ir source with regard to clinical aspects. Because of inherent differences in physical characteristics between these isotopes, small but statistically significant differences in dose distributions are seen. However, many of these differences in dose delivery to CTV can be reduced by treatment planning optimization techniques. Based on the 3D dosimetric analysis of patient plans considered in this study, ^{60}Co source can be used as a viable alternative to ^{192}Ir source in HDR interstitial brachytherapy for breast cancer. The outcome of ^{60}Co TG-43 based dosimetry is the amount of reduction it achieved, which was matched with the ^{192}Ir TG-43 based calculation through optimization. As the variation pertaining to target volume is within 3% dose difference, ^{60}Co isotope can be used for HDR interstitial breast brachytherapy because of its long half-life, logistic advantages in procurement, infrequent need of source replacement and disposal of used source.

Conflict of interest

None declared.

Financial disclosure

None declared.

REFERENCES

1. Kubaszewska M, Dymnicka M, Skowronek J, et al. CT image-based interstitial HDR brachytherapy boost in the conservative treatment of stage I–II breast cancer – introducing the procedure. *Rep Pract Oncol Radiother* 2008;**13**(5):227–39.
2. Salminen EK, Kiel K, Ibbott GS, et al. International conference on advances in radiation oncology (ICARO): outcomes of an IAEA meeting. *Radiat Oncol* 2011;**6**:1–9.
3. Henschke UK, Hilaris BS, Mahan GD. Remote after loading with intracavitary applicators. *Radiology* 1964;**83**:344–5.
4. Davis SD, Parker W, Evans MD. Using mean dose rate to compare relative dosimetric efficiency with respect to source type and source change schedules for HDR brachytherapy. *J Appl Clin Med Phys* 2013;**14**(6).
5. Strohmaier S, Zwierzchowski G. Comparison of ^{60}Co and ^{192}Ir sources in HDR brachytherapy. *J Contemp Brachyther* 2011;**3**:199–208.
6. Granero D, Perez-Calatayud J, Ballester F. Technical note: Dosimetric study of a new Co-60 source used in brachytherapy. *Med Phys* 2007;**34**:3485–8.
7. Venselaar JL, van der Giessen PH, Dries WJ. Measurement and calculation of the dose at large distances from brachytherapy sources: Cs-137, Ir-192 and co-60. *Med Phys* 1996;**23**:537–43.
8. Richter J, Baier K, Flentje M. Comparison of 60cobalt and 192iridium sources in high dose rate afterloading brachytherapy. *Strahlenther Onkol* 2008;**184**:187–92.
9. Park D-W, Kim YS, Park SH, et al. A comparison of dose distributions of HDR intracavitary brachytherapy using

different sources and treatment planning systems. *Appl Radiat Isot* 2009;**67**:1426–31.
10. Andrássy M, Niatsetsky Y, Pérez-Calatayud J. Co-60 versus Ir-192 in HDR brachytherapy: scientific and technological comparison. *Rev Fis Med* 2012;**13**(2):125–30.
11. Gifford KA, Horton Jr JL, Wareing TA, et al. Comparison of a finite-element multigroup discrete-ordinates code with Monte Carlo for radiotherapy calculations. *Phys Med Biol* 2006;**51**:2253.
12. Van der Laarse R. The stepping source dosimetry system as an extension of the Paris system. In: Mould RF, Battermann JJ, Martinez AA, Speiser BL, editors. *Brachytherapy from radium to optimization*. Veenendaal: Nucletron International BV; 1994. p. 342.
13. Baltas D, Kolotas C, Geramani K, et al. A conformal index (COIN) to evaluate implant quality and dose specification in brachytherapy. *Int J Radiat Biol Phys* 1998;**40**:515–24.
14. Papagiannis P, Baltas D, Granero D, et al. Radiation transmission data for radionuclides and materials relevant to brachytherapy facility shielding. *Med Phys* 2008;**35**: 4898–906.
15. Palmer A, et al. 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 Brachyther* 2012;**4**(1):52–9.
16. 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**: 633–74.
17. Candela C, Perez-Calatayud J, Ballester F, et al. Calculated organ doses using Monte Carlo simulations in a reference male phantom undergoing HDR brachytherapy applied to localized prostate carcinoma. *Med Phys* 2013;**40**.