



SSI report

# SSI Rapport

## 2007:13

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### *Dosimetry audit on the accuracy of $^{192}\text{Ir}$ brachytherapy source strength determinations in Sweden*

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Swedish Radiation Protection Authority

# SSI's Activity Symbols



## Ultraviolet, solar and optical radiation

Ultraviolet radiation from the sun and solariums can result in both long-term and short-term effects. Other types of optical radiation, primarily from lasers, can also be hazardous. SSI provides guidance and information.

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## Solariums

The risk of tanning in a solarium are probably the same as tanning in natural sunlight. Therefore SSI's regulations also provide advice for people tanning in solariums.

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## Radon

The largest contribution to the total radiation dose to the Swedish population comes from indoor air. SSI works with risk assessments, measurement techniques and advises other authorities.

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## Health care

The second largest contribution to the total radiation dose to the Swedish population comes from health care. SSI is working to reduce the radiation dose to employees and patients through its regulations and its inspection activities.

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## Radiation in industry and research

According to the Radiation Protection Act, a licence is required to conduct activities involving ionising radiation. SSI promulgates regulations and checks compliance with these regulations, conducts inspections and investigations and can stop hazardous activities.

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## Nuclear power

SSI requires that nuclear power plants should have adequate radiation protection for the general public, employees and the environment. SSI also checks compliance with these requirements on a continuous basis.

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## Waste

SSI works to ensure that all radioactive waste is managed in a manner that is safe from the standpoint of radiation protection.

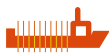
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## Mobile telephony

Mobile telephones and base stations emit electromagnetic fields. SSI is monitoring developments and research in mobile telephony and associated health risks.

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## Transport

SSI is involved in work in Sweden and abroad to ensure the safe transportation of radioactive substances used in the health care sector, industrial radiation sources and spent nuclear fuel.

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## Environment

"A safe radiation environment" is one of the 15 environmental quality objectives that the Swedish parliament has decided must be met in order to achieve an ecologically sustainable development in society. SSI is responsible for ensuring that this objective is reached.

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## Biofuel

Biofuel from trees, which contains, for example from the Chernobyl accident, is an issue where SSI is currently conducting research and formulating regulations.

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## Cosmic radiation

Airline flight crews can be exposed to high levels of cosmic radiation. SSI participates in joint international projects to identify the occupational exposure within this job category.

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## Electromagnetic fields

SSI is working on the risks associated with electromagnetic fields and adopts countermeasures when risks are identified.

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## Emergency preparedness

SSI maintains a round-the-clock emergency response organisation to protect people and the environment from the consequences of nuclear accidents and other radiation-related accidents.

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## SSI Education

is charged with providing a wide range of education in the field of radiation protection. Its courses are financed by students' fees.

**EDITORS / REDAKTÖRER :** Åsa Carlsson Tedgren

**TITLE / TITEL:** Dosimetry audit on the accuracy of  $^{192}\text{Ir}$  brachytherapy source strength determinations in Sweden / Kartläggning av status för dosimetri inom brachyterapi vid svenska sjukhus.

**DEPARTMENT / AVDELNING:** Department of Occupational & Medical Exposures / Avdelningen personal- och patientstrålskydd.

**SUMMARY:** The absorbed dose delivered to the patient in brachytherapy is directly proportional to the source strength in terms of the reference air-kerma rate (RAKR). Verification of this quantity by the hospitals is widely recognized as an important part of a quality assurance program. An external audit was performed on behalf of the Secondary Standard Dosimetry Laboratory at the Swedish Radiation Protection Authority (SSI).

The aim was to investigate how accurately the source-strength in  $^{192}\text{Ir}$  brachytherapy is determined at Swedish hospitals. The SSI reference well-type ion chamber and calibrated equipment were used to measure the RAKR of an  $^{192}\text{Ir}$  source in each of the 14 Swedish afterloading units. Comparisons with values determined by vendors and hospitals were made. Agreement in values of RAKR as determined by SSI, hospitals and vendors were in all cases within the  $\pm 3\%$  uncertainty (at a coverage factor of  $k=2$ ), typically guaranteed by the vendors. The good agreement reflects the robustness and easy handling of well-type chambers designed for brachytherapy in use by all Swedish hospitals. The  $^{192}\text{Ir}$  calibration service planned at SSI will solve the hospitals current problem with recalibration of equipment. SSI can also advise hospitals to follow the IAEA recommendations for measurement techniques and maintenance of equipment.

It is worthwhile for the hospitals to establish their own ratio (or deviation) with the vendor and follow it as function of time. Such a mean-ratio embeds systematic differences of various origins and have a lower uncertainty than has the RAKR alone, making it useful for early detection of problems with equipment or routines. SSI could also define requirements for the agreement between source strengths as determined by hospitals and vendors and couple this to an action plan, dependent on level of disagreement, and some kind of reporting to SSI.

**SAMMANFATTNING:** Vid strålbehandling med brachyterapi är den absorberade dosen till patienten direkt proportionell mot den använda strålkällans styrka, mätt i enheten referensluftkermarat (RAKR). En viktig del i kvalitetssäkring av brachyterapi är därför att noggrant bestämma denna storhet för varje strålkälla som tas i bruk. Målet med detta arbete har varit att undersöka noggrannheten i bestämningen av RAKR för brachyterapi med  $^{192}\text{Ir}$  vid svenska sjukhus.

Undersökningen har gjorts via externa kontroller. Kalibrerad utrustning från Riksmätplatsen vid Statens Strålskyddsinstitut (SSI) har använts för att bestämma RAKR för en strålkälla i var och en av de 14 efterladdningsenheter för  $^{192}\text{Ir}$ -terapi som finns i Sverige. Resultaten har jämförts med de värden som sjukhusen själva har mätt upp samt med de värden som källtillverkarna angivit. Värden uppmätta med SSI:s utrustning överensstämde för alla enheter inom 3 % med de värden som uppmätts av sjukhusen och angivits av källtillverkarna (som typiskt garanterar en noggrannhet av 3 % vid  $k=2$  eller 95 % konfidensintervall). Den goda överensstämmelsen speglar hur stabila och robusta de håljonkammare som används på alla svenska sjukhus är. Den vid SSI planerade kalibreringsservicen för håljonkammare i  $^{192}\text{Ir}$  kommer att lösa det problem med förnyad kalibrering som sjukhusen i Sverige för närvarande har. SSI kan bistå sjukhusen med råd att följa procedurer för användande och konstanskontroll av utrustning som ges av IAEA.

Sjukhusen kan också uppmanas att etablera sin egen kvot (eller avvikelse) med respektive källtillverkarens RAKR-värde. En sådan kvot speglar systematiska skillnader av olika slag och har därför en lägre osäkerhet än RAKR ensam. Avvikelser i den etablerade kvoten (differensen) kan användas för att tidigt upptäcka problem med utrustning och mätrutiner på sjukhuset eller hos tillverkaren. SSI kan även formulera krav på överensstämmelse i RAKR mellan sjukhus och källtillverkare och koppla dessa krav till en handlingsplan beroende på avvikelens storlek samt med rapportering till SSI.

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*The conclusions and viewpoints presented in the report are those of the authors and do not necessarily coincide with those of the SSI.*

Författarna svarar själva för innehållet i rapporten.



Statens strålskyddsinstitut  
Swedish Radiation Protection Authority



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# 1. Introduction

Brachytherapy is radiation therapy applied through the insertion of sealed, radioactive sources within the patient. It is applied as intracavitary, intraluminal or interstitial therapy meaning placement within a natural body cavity, a lumen or through surgical insertion, respectively.

Use of brachytherapy has increased in Sweden during last years. Its main advantage is ability to give a highly localised dose to the target while irradiating small volumes of normal tissues. It is applied as only treatment or as a boost to external beam therapy for gynaecological malignancies, cancer of prostate, lung, head- and neck, and for certain paediatric malignancies.

The most common isotope is  $^{192}\text{Ir}$ , having a half-life of 74 days and a mean photon energy of around 350 keV. In Sweden the  $^{192}\text{Ir}$  treatments are carried out using remotely controlled after-loading equipment (one exception occurs at the Sahlgrenska hospital in Gothenburg where around 10 implants a year are performed with manually inserted  $^{192}\text{Ir}$ -wires of low dose rate). With remote afterloading, a single miniature source of high activity is stored in a radiation-safe afterloader. During treatment the source is “stepped” remotely through source-channels, pre-inserted in the patient.

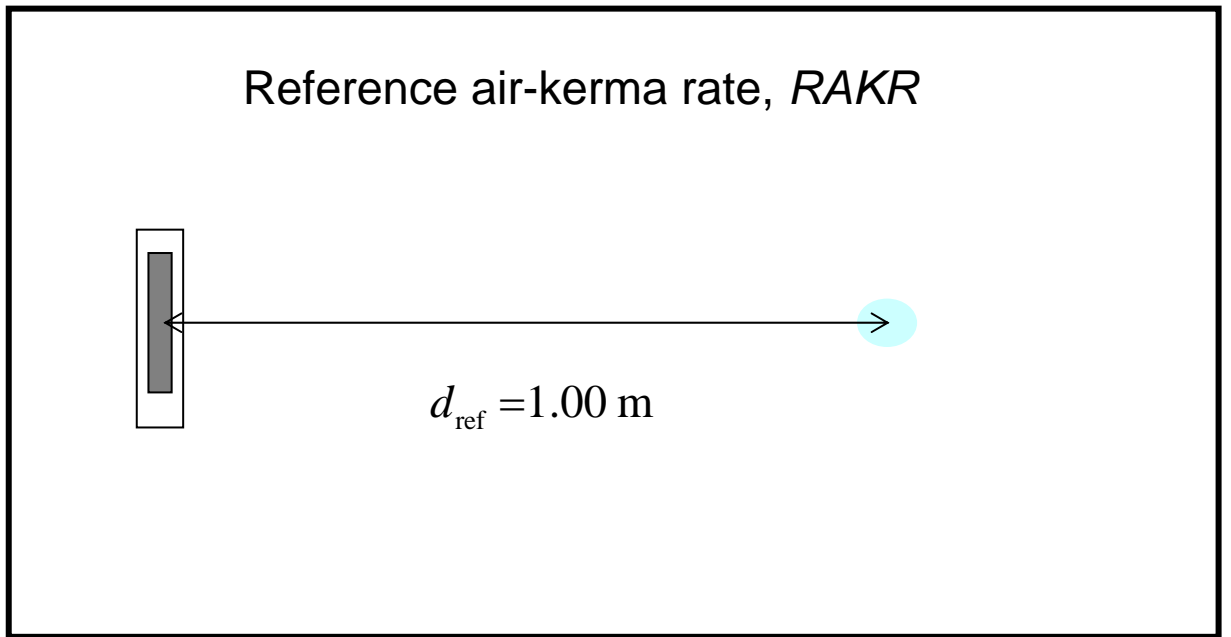
In radiation therapy, the requirement on accuracy in the determination of absorbed doses is high due to steep dose-response curves in tumours and normal tissues ((Brahme, 1984)). The strength of brachytherapy sources is determined by the quantity “reference air kerma rate”, *RAKR*. The absorbed dose delivered to patients is proportional to the *RAKR* of the source, through the dose calculation formalism used in brachytherapy treatment planning systems. The half-life of  $^{192}\text{Ir}$  is 74 days and hospitals therefore renew their sources with intervals of around 3 months. Each new source comes with a certificate on which the source vendor states the source strength (usually with an accuracy of  $\pm 5\%$  at a confidence limit of 99,7%). An independent check of the strength of each source by the end user (i.e. the hospitals) before taking it into use is widely recommended as an important part of a quality assurance program (IAEA (2002), Nath *et al.* (1997), Venselaar and Pèrez-Calatayud (2004)). Using appropriate equipment, this assures traceability to dosimetric standards and an independent check of the value stated by the vendor.

In Sweden,  $^{192}\text{Ir}$ -brachytherapy is performed at 7 hospitals using 14 afterloading units. The current project is performed on behalf of the Swedish Radiation Protection Authority (SSI) with the aim of performing a dosimetry audit determining the source strength for a source in each of these units. The audit is carried out by the author (trained at SSI's Secondary Standard Dosimetry Laboratory) in collaboration with the personnel at SSI and using their calibrated equipment. The source strengths, as determined with SSI's equipment, are compared to values specified by vendors and measured by hospitals. Through the site visits, information about the status of the hospital's equipment and its handling were also gathered.

## 2. Theory

### 2.1 Source strength specification

The European recommendation for specifying brachytherapy source strength is as the “reference air kerma rate”, *RAKR* (ICRU (1985), ICRU (1997)). The *RAKR* is the air-kerma rate to air in air at a reference distance of 1 meter,  $d_{\text{ref}}$ , corrected for attenuation and scattering. *RAKR* refers to the quantity as determined along the perpendicular bisector of the source (commonly shaped as a cylinder), see Figure 1.



**Figure 1** Brachytherapy source strength is specified by the reference air-kerma rate, *RAKR* which is the kerma rate in air to air, at 1 meter along the perpendicular bisector of the source corrected for attenuation and scattering.

In North America the source strength is instead specified through the “air-kerma strength”,  $S_K$ , (Rivard *et al.* (2004)). The air-kerma strength is the air-kerma rate in air at a distance  $d$  from the source, corrected for scattering and attenuation and multiplied with that distance squared,  $d^2$ . The two definitions are related through:

$$RAKR = S_K / d_{\text{ref}}^2 \quad (1)$$

and hence, since  $d_{\text{ref}}$  is unity (1 m), numerically equal.

The dose calculation formalism in use by most treatment planning systems applies a parameterization of the single-source dose distribution in water as recommended by the Task Group # 43 of the American Association of Physicists in Medicine (Rivard *et al.* (2004)). The dose rate  $\dot{D}$  in water to a point at distance  $r$  and at polar angle  $\theta$  from the source is in this way obtained through:



$$\dot{D}(r, \theta) = S_K \Lambda \frac{G(r, \theta)}{G(r_0, \theta_0)} g(r) F(r, \theta) \quad (2)$$

where  $S_K$  is the air-kerma strength of the actual source and the remaining parameters are predetermined (through experimentally verified Monte Carlo simulations) according to rigorous rules set up and supplied in the TG43-report. From Eq. (2) it is clear that the dose delivered to the patient is directly proportional to the air-kerma strength of the source,  $S_K$ , or equivalently to the *RAKR* according to Eq. (1).

## 2.2 Standards for $^{192}\text{Ir}$

Until recently no primary standard for high dose rate (HDR)  $^{192}\text{Ir}$  was available. The mean energy of  $^{192}\text{Ir}$  (350 keV) falls in between those of existing standards at most calibration laboratories. Several laboratories offer calibrations of ion chambers for  $^{192}\text{Ir}$  based on various methods of interpolation between radiation qualities below and above the mean energy of  $^{192}\text{Ir}$  (Goetsch *et al.* (1991), Büermann *et al.* (1994), van Dijk *et al.* (2004), Douysset *et al.* (2005)). A primary standard, in form of a graphite ion chamber, has recently been developed at the National Physics Laboratory (NPL) in Great Britain (Sander and Nutbrown (2006)). NPL started to offer calibrations against their standard in 2005.

The SSI well-chamber, used throughout this audit is a “HDR 1000 Plus”, manufactured by Standard Imaging Inc. It is designed for use in brachytherapy and complies with IAEA recommendations on suitable equipment (IAEA (2002)). The chamber was bought in 2002 with a calibration factor from the Accredited Dosimetry Calibration Laboratory at the University of Wisconsin in USA (UWADCL). UWADCL is a SSDL and uses the interpolation method by Goetsch *et al.* (1991) as reference for  $^{192}\text{Ir}$  calibrations. The SSI chamber was later (in 2005) calibrated against the NPL primary standard. The two different  $^{192}\text{Ir}$  calibration factors for the SSI chamber are given in Table 1.

**Table 1** Data for the two calibrations of the SSI chamber. The calibration factor from UWADCL has been recalculated to be valid at the reference conditions of 20 °C and 101,325 kPa. The uncertainty in calibration factors from NPL has since 2005 been further reduced and is now  $\pm 0,8\%$  at  $k=2$  (Sander and Nutbrown (2006)).

Calibration laboratory	Calibration factor	Uncertainty at $k=2$	Source type
UWADCL (2002)	$N_{S_K} = 129,4$ [Gym <sup>2</sup> /C]	$\pm 2,5 \%$	VariSource HDR
NPL (2005)	$N_{RAKR} = 128,4$ [Gy/C]	$\pm 1,3 \%$	MicroSelectron-classic HDR

The source type used in the calibration is also given in Table 1. Being strict, a calibration is valid for that source type only. Since the *RAKR* and  $S_K$  refer to the value along the perpendicular bisector of the source (see Figure 1), the transfer of the initial, free-in-air measurement to the close-to  $4\pi$ -geometry of the well-chamber (performed by the calibration laboratory) can yield differences due to source design. A study on this matter showed

that differences between various common HDR  $^{192}\text{Ir}$  sources are lower than 2% (Stump *et al.* (2002)). Uncertainties of calibration factors based on interpolation techniques are typically higher than 2% and it was hence concluded that factors for HDR  $^{192}\text{Ir}$  obtained with one type of source can be used for other fabricates without further corrections. For  $^{192}\text{Ir}$ , the source anisotropy is mainly determined by the length of the active material and most HDR sources are of similar dimensions. Some of the weaker PDR sources (PDR stands for pulsed dose rate and is an alternative treatment technique) have a shorter active length which makes them irradiate more isotropic. Differences in well-chamber calibration factor for these sources are probably higher than was seen by Stump *et al.* (2002) in comparing HDR-sources, however no study on this issue exists. The main advantage with a primary standard over those based on interpolation techniques is the reduced uncertainty of the calibration factor (c.f. Table 1) which might make it possible to reveal differences due to source design more careful in the future.

## 2.3 Recommendations on equipment and its maintenance

The International Atomic Energy Agency (IAEA) has published a report that provides detailed advices on calibration, equipment, measurement techniques, constancy controls and recalibration intervals (IAEA, (2002)). Secondary Standard Dosimetry Laboratories (SSDLs) and hospitals are both recommended to use well-type ionisation chambers as detectors for brachytherapy source strength. The chambers should be designed specially for brachytherapy and be open to the atmosphere. Hospitals are recommended to recalibrate their chambers at a SSDL with 2 years interval and to perform regular constancy controls of their chambers using long-lived check-sources. SSDLs are recommended to recalibrate at a Primary Standard Dosimetry Laboratory (PSDL) with 2 years interval. This interval might be prolonged to 5 years if the SSDL can assure constancy of the chamber at energies both below and above that of the  $^{192}\text{Ir}$  mean energy. The main photon emission lines of  $^{192}\text{Ir}$  fall in between 50 keV and 700 keV and use of  $^{241}\text{Am}$  and  $^{137}\text{Cs}$  as check-sources) is suggested (mean energies 60 keV and 662 keV, respectively).

## 3. Methods

### 3.1 Equipment and constancy control routines

The equipment used in the current audit is listed in Table 2.

The constancy of the equipment was checked before and after each external site visit. The thermometer, pressure meter and electrometer were checked through comparison with calibrated, stationary equipment at SSI. The stability of the well-type chamber was verified through irradiation in SSI's  $^{60}\text{Co}$  therapy level beam. A routine for constancy control with a  $^{137}\text{Cs}$  check-source for internal irradiation was also developed. The  $^{137}\text{Cs}$  source-holder is, however, currently broken which is why no check with this system was made

**Table 2** Equipment used by SSI.

Equipment	Name and serial number
Well-type ion chamber	Standard Imaging "HDR 1000+", s/n A022896
Thimble ion chamber	Farmer NE2571, s/n 2565
Electrometer	Keithley 6517A, s/n 0945145
Thermometer	Vaisala, s/n 55110001
Pressure meter	Paulin , s/n 10025

during the audit period. To comply with IAEA recommendations for SSDLs, regarding constancy check routines at energies below and above the mean energy of  $^{192}\text{Ir}$ , a routine for checking the stability of the well-chamber in a  $^{241}\text{Am}$  external beam was developed. Finally, at each hospital-visit, at least one source was measured with a redundant system consisting of a Farmer chamber in a PMMA-phantom. The ratio between the well-chamber and this system was used as an on-site check of the reference well-chamber.

### 3.2 Chamber correction factors

The well-type chamber is open to the atmosphere and corrections for temperature and pressure were performed through multiplying the measured current by the correction factor:

$$k_{T,P} = \frac{(T + 273,15)}{(T_0 + 273,15)} \cdot \frac{P_0}{P} \quad (3)$$

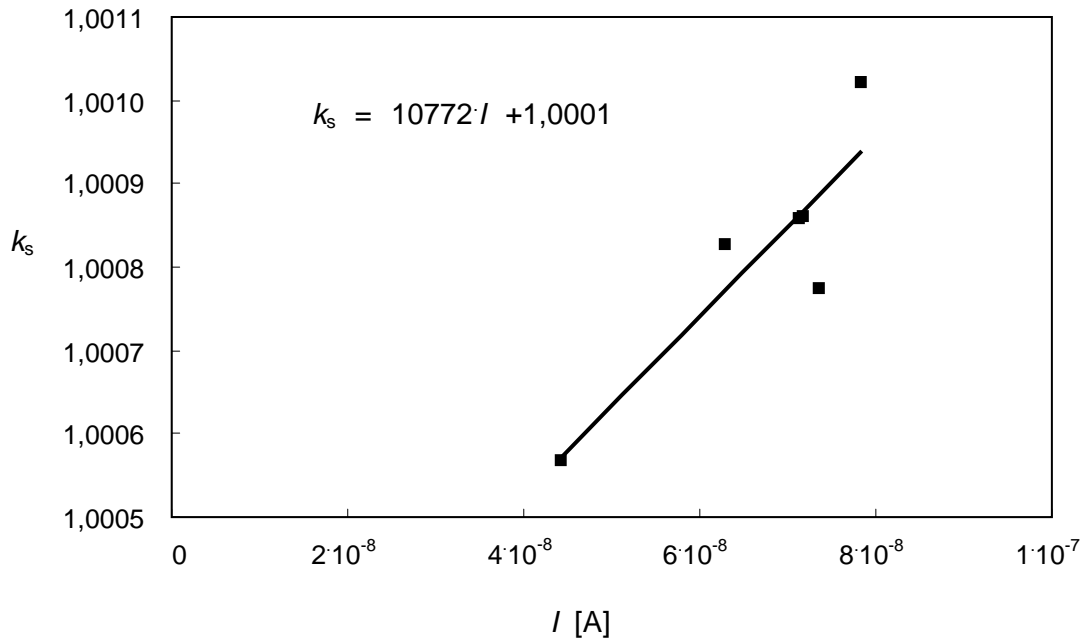
where  $T$  is the temperature in  $^{\circ}\text{C}$  and  $P$  is the pressure in kPa,  $T_0$  and  $P_0$  are the reference conditions (  $20^{\circ}\text{C}$  and 101,325 kPa).

The recombination correction factor,  $k_s$ , was determined using the two-voltage technique, according to

$$k_s = \frac{1}{\frac{4}{3} - \left( \frac{I_{300V}}{3I_{150V}} \right)} \quad (4)$$

where  $I_{300V}$  is the ionization current at the chamber's working potential 300 V and  $I_{150V}$  the current obtained at halved working potential i.e. 150 V. The  $k_s$  as function of ionization current obtained in measuring a number of sources of varying strength is shown in Figure 2 together with a linear fit.

During the audit, the linear fit of Figure 2 was used to determine the recombination factor to correct currents when measuring HDR sources. For PDR sources, producing around ten times lower currents, no correction for recombination was applied.



**Figure 2** Recombination correction factors as determined with the two-voltage method at different currents produced by HDR sources of varying strength and a linear fit to the data.

### 3.3 On-site measurements

The SSI on-site measurements comply with recommendations given by IAEA (IAEA (2002)). The equipment was always left in the treatment room on the day before measurements to reach thermal equilibrium with the surrounding. The air-temperature was determined within the well of the chamber. This was found important since the equipment come slowly into thermal equilibrium with the surrounding. A change in air-temperature of the room might not be fully reflected in the equipment until after several hours (see e.g. Figure 3.5 on page 48 in Venselaar and Pèrez-Calatayud (2004)). Storage within the room since the day before measurements does not ensure equivalence between the temperature in the surrounding air and that in the well of the chamber since there can be temperature gradients within the room. Differences can exceed one degree when the placement during storage does not coincide exactly with that during measurements. We have once encountered a difference of several degrees between the chamber and the surrounding air (not during this audit however). This occurred after a prostate treatment in which heated air was circulated beneath the quilt of the patient while the chamber was stored in a cupboard of the room.

The electrometer was turned on for at least one hour before measurements and the high voltage for at least 30 minutes. A system of low-scattering plastic boxes was used to get the centre of the chamber up at a distance of one meter above the floor. Care was taken to avoid walls and other equipment of the room as much as possible, to reduce scattering from these objects to contribute to the measured signal.



**Figure 3** The SSI well-type ion chamber on top of the low-scattering plastic boxes used to position the centre of the chamber at 1 meter above the floor.



**Figure 4** The Farmer-in-Phantom system used as an on-site constancy control of the well-type chamber. The plastic source-channel used to guide the source from the afterloading equipment to the irradiation position is also seen.

The chambers were pre-irradiated for a minimum of ten minutes before taking measurements. The point of maximum response was determined and three repeated source insertions were made. The electrometer was used in current-mode and therefore no account for source-transit time was needed. To assure the reproducibility in position it was checked that current-differences between the three insertions was less than 0,3% (IAEA (2002)). During each insertion the current was read on regular intervals at least ten times and lack of drift in the signal was assured. The time specified by date, hour and minute was used in decay corrections. Measurements were in all but one site done using a plastic source-channel to guide the source, as required on the NPL calibration-certificate. At one site problems with determining the length of the plastic channel arose and we had to use a

prostate needle of stainless steel (in use by this hospital). At a later time and another hospital, measurements to determine a correction factor, accounting for the difference between use of a stainless steel needle and a plastic channel, were performed. This resulted in that a correction of 1,007 was applied to the signal determined using the stainless steel needle.

### 3.4 Estimation of uncertainty

The uncertainty in the determination of the ionization current and the reference air-kerma rate (*RAKR*) is determined following recommendations in the “Guide to the uncertainty in measurement” (GUM), ISO (1995)), for details see the Appendix.

## 4. Results

### 4.1 Inventory of $^{192}\text{Ir}$ sources and overview of equipment and procedures at Swedish hospitals

Brachytherapy with  $^{192}\text{Ir}$  is performed at 7 hospitals in Sweden, using in total 14 after-loading units, see Table 3.

**Table 3** Inventory of the Swedish  $^{192}\text{Ir}$  after loading units. There are 9 HDR and 5 PDR units.

Hospital	Vendor	Source
Karolinska, Radiumhemmet	Varian	Varisource , HDR
-“-	Nucletron	Microselectron-classic, HDR
-“-	Nucletron	MicroSelectron-v2, PDR
-“-	Nucletron	MicroSelectron-classic, PDR
Karolinska, Södersjukhuset	Varian	VariSource, HDR
Uppsala	Nucletron	MicroSelectron-classic, HDR
Linköping	Varian	GammaMed Plus, HDR
Örebro	Nucletron	MicroSelectron-v2, HDR
-“-	Nucletron	HDRM MicroSelectron-v2, HDR
-“-	Nucletron	MicroSelectron-classic, PDR
-“-	Nucletron	MicroSelectron-classic, PDR
Lund	Varian	GammaMed Plus, HDR
Göteborg	Varian	GammaMed 12i, HDR
-“-	Varian	GammaMed 12i, PDR

All the hospitals have well-type ionisation chambers that fulfil the IAEA recommendations (IAEA (2002)). All except one have calibration factors traceable to UWADCL. One hospital relies instead on their own free-in-air measurements and interpolation technique (Drugge (1995)). This hospital is traceable to SSI through the interpolation qualities. The calibration factors in use are the ones obtained when purchasing the chambers, in some case as old as 7 years. No hospital has sent their chamber abroad for recalibration but await SSI to start offering this service.

All the Swedish hospitals measure the strength of each new  $^{192}\text{Ir}$  source. All, except one use the value determined by the vendor in the treatment planning system, i.e. the own

measurements are for verification purposes. Among the ones verifying the vendor value there is no strict tolerance level on the agreement although most hospitals tell they aim for and most often get an agreement within  $\pm 1\%$ .

There are large differences in how the hospitals perform their measurements, both regarding the geometrical setup and in their handling of the equipment. Most hospitals fulfil geometrical requirements on placing the chamber away from any walls and the floor while measuring. One hospital has their chamber permanently mounted on the wall in a corner of the treatment room. This placement is likely to increase the amount of scattered radiation reaching the chamber ((Podgorsak *et al.*, 1992)). The hospital is aware of this but has not investigated the magnitude of the effect. Many calibration certificates require use of a plastic catheter for guiding the source to the chamber and most hospitals do so, however, some instead use a needle of stainless steel (of the type used for prostate treatments). Some hospitals leave the chamber to come into thermal equilibrium with the surrounding, allow time for stabilisation with high voltage supply on and pre-irradiate it before taking measurements. Others take measurements almost directly without precautions on stabilisation etc. Most hospitals determine the point of maximum response<sup>1</sup> for the chamber for each new source and repeat source insertions to assure positional accuracy (as recommended by e.g. the IAEA) whereas some trust earlier determinations of the point for maximum response and do not repeat source insertions.

Routines and methods for constancy control of the hospital's chambers also vary. One hospital has a  $^{137}\text{Cs}$  check-source for internal irradiation, others irradiate their chambers in an external  $^{60}\text{Co}$  field, some do additional measurements with a redundant detector system whereas some do not check the constancy of their equipment at all. Among the hospitals with routines, some check the constancy of their equipment before each source strength determination whereas some only occasionally sometimes with intervals longer than one year.

Routines for controlling and calibrating other equipment (electrometers, thermometers, pressure meters) were not investigated.

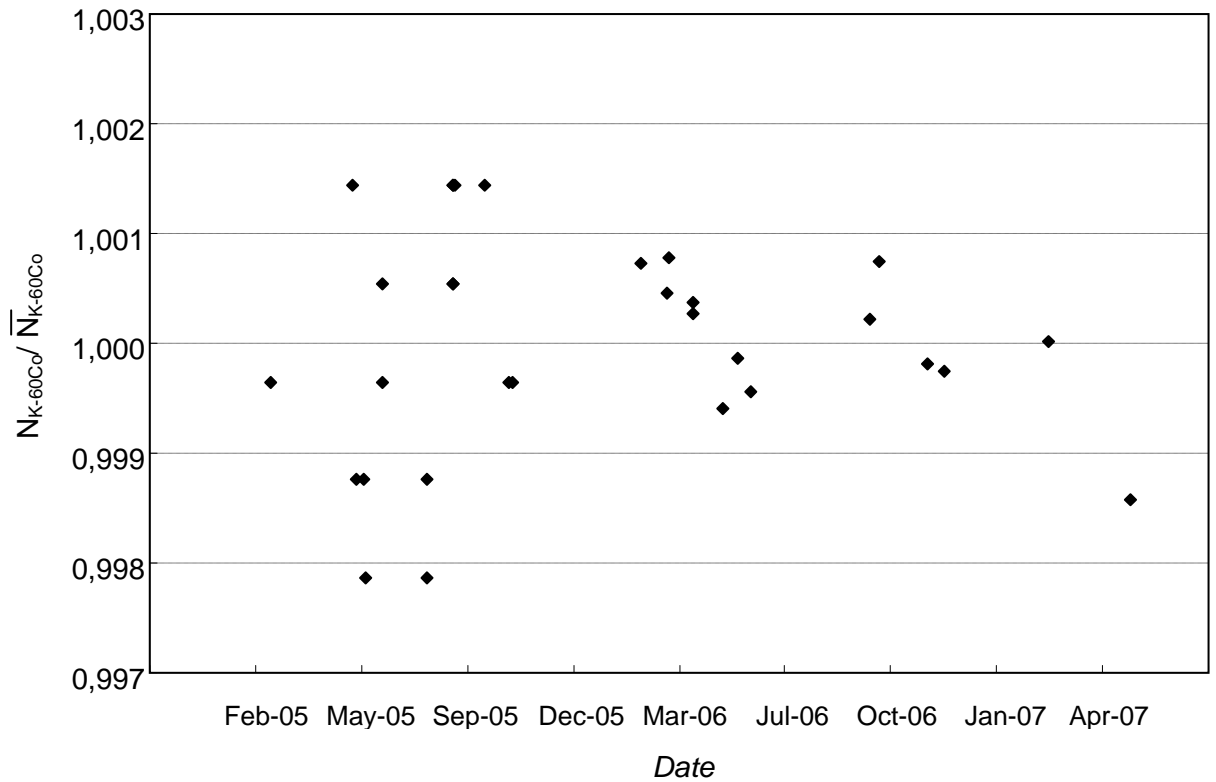
## 4.2 Constancy of the SSI equipment

The stability of the SSI well-type chamber, as checked in the SSI external therapy level  $^{60}\text{Co}$  beam, is shown in Figure 5.

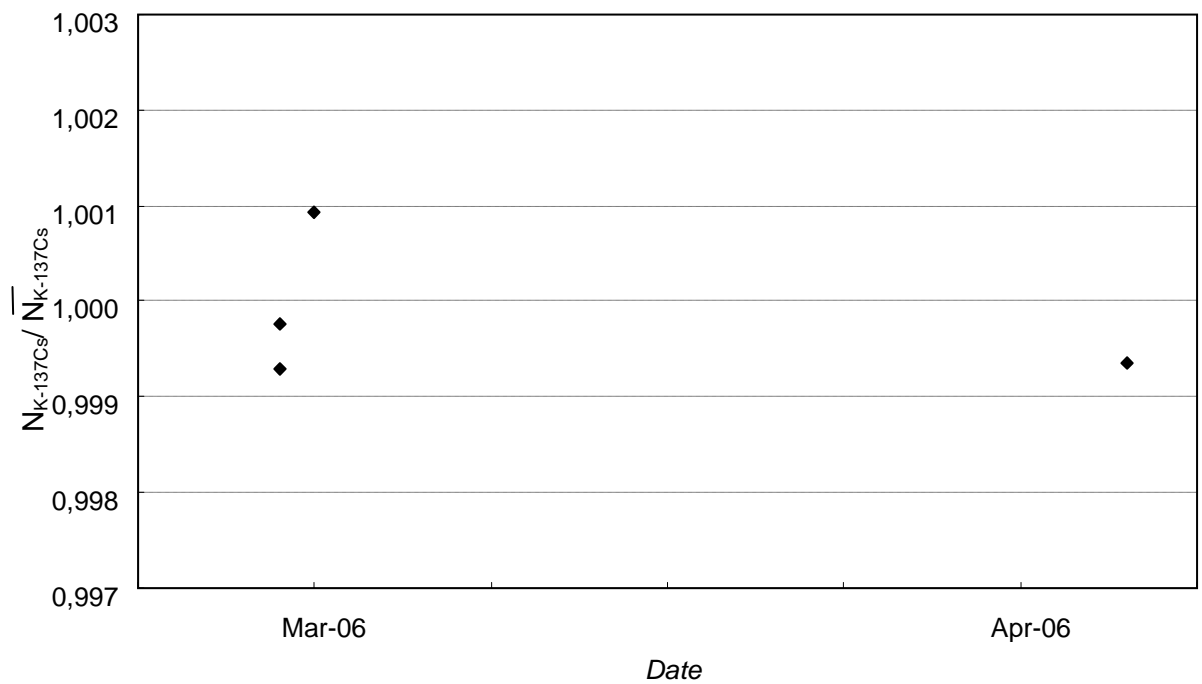
Although the well-type chamber is permanently stored in the same room as the  $^{60}\text{Co}$  unit, the difference in temperature from the storage cupboard to the placement during irradiation is often 1 °C. Starting in 2006, the temperature is measured within the well of the chamber. The increased stability of the signal seen since 2006 is explained by the improved control of the temperature.

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<sup>1</sup> The point of maximum response of a well-type ionization chamber corresponds to the position of the source within the well that give raise to the highest signal. In most chambers there is a region of slowly varying sensitivity around this point which reduces positional uncertainty. The calibration of the chamber is usually valid for the point of maximum response.



**Figure 5** Decay-corrected signal of the well-chamber normalised to its mean value obtained by external irradiation in SSI's therapy level  $^{60}\text{Co}$  beam.

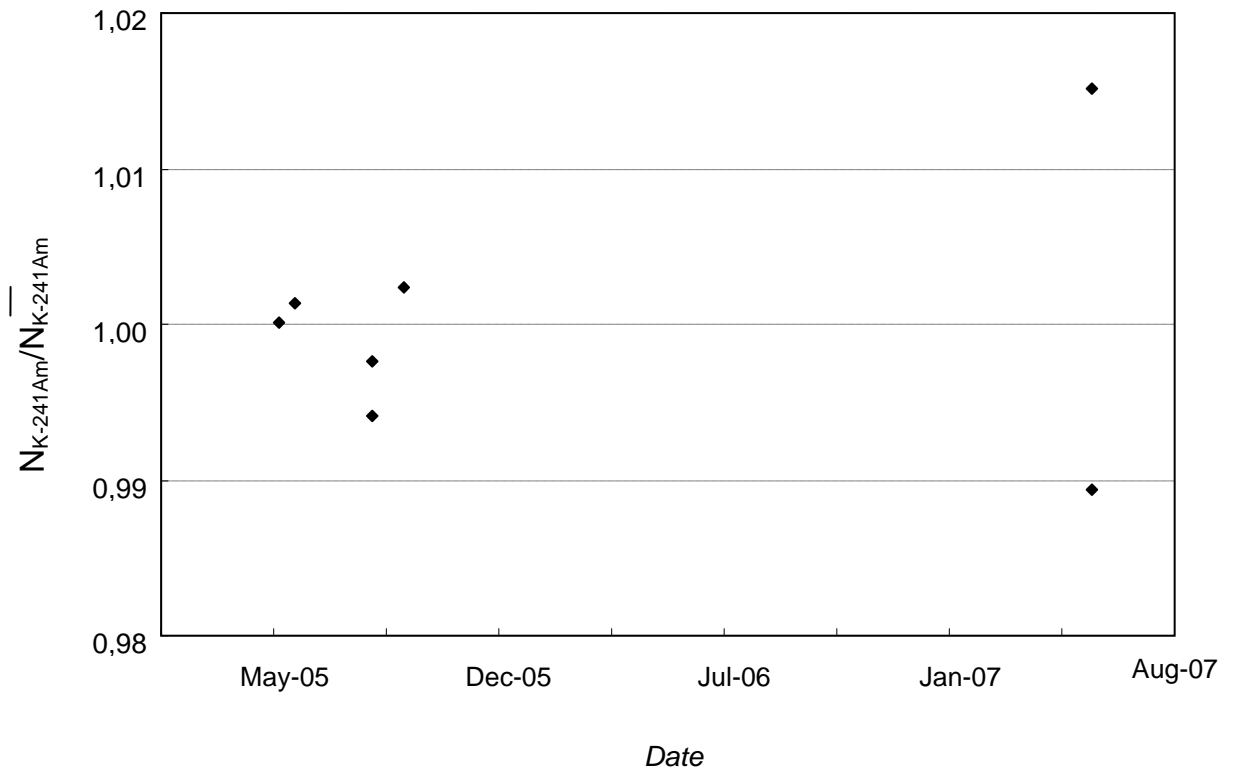


**Figure 6** Decay-corrected signal of the well-chamber normalised to its mean value, obtained by internal irradiation by the  $^{137}\text{Cs}$  check-source.



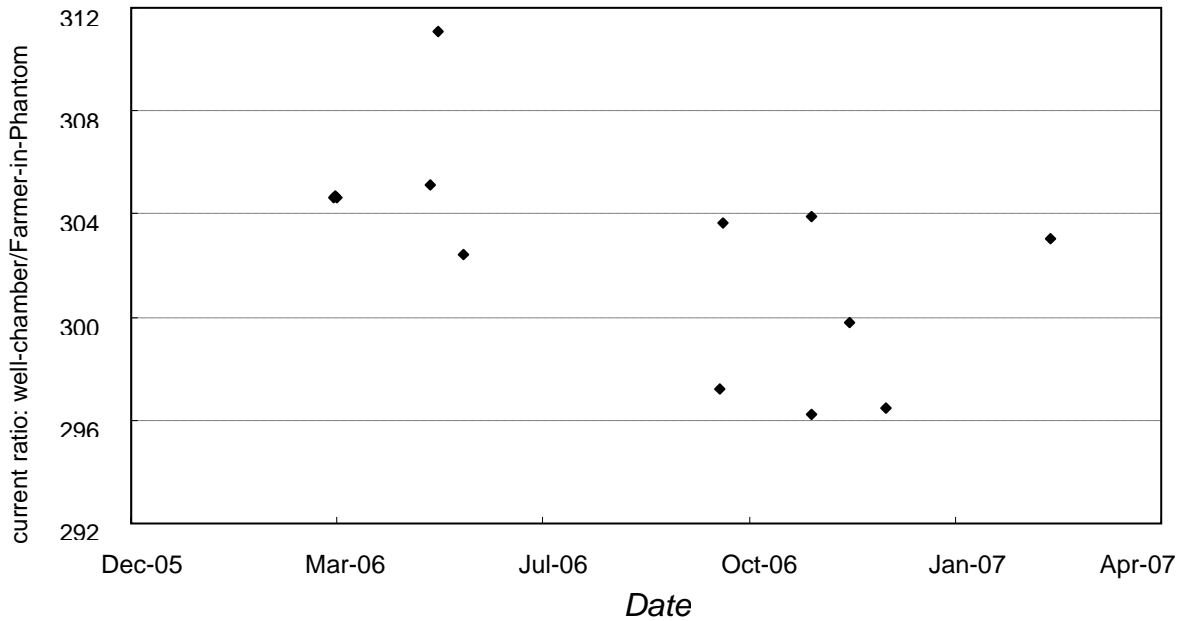
Figure 6 shows similar results using the  $^{137}\text{Cs}$  check source for internal irradiation of the chamber. The lack of results after April 2006 is due to a broken source holder that has not yet been repaired.

Figure 7 shows results of checking the constancy of the chamber in an external  $^{241}\text{Am}$  beam. The uncertainty of this routine is higher because the  $^{241}\text{Am}$  source is weak (thus producing a very low current in the chamber) and since the positioning is less precise. SSI normally uses the  $^{241}\text{Am}$  beam to calibrate instruments aimed for radiation protection purposes.



**Figure 7** Decay-corrected signal of the well-chamber normalised to its mean value, obtained by external irradiation in SSI's radiation protection-level  $^{241}\text{Am}$  beam.

Figure 8 shows the ratio of the currents, as measured by the well-type chamber to that of the Farmer-in-phantom, for different  $^{192}\text{Ir}$  sources. This ratio was determined at each site visited and used as an extra, on-site constancy control of the well-chamber. The standard deviation in the ratio is 1,2% which is comparatively high and depends on suboptimal properties of the phantom. The phantom could be improved by increasing the distance between the Farmer chamber and the source (from today's 2 cm to around 5 cm, as used in most commercial phantoms), by drilling a straighter hole for the source-channel and by constructing inserts for source channels of varying diameter. Even though some properties of the PMMA-phantom are not optimal it is valuable as an on-site check of the reference equipment.



**Figure 8** The ratio of currents for  $^{192}\text{Ir}$  irradiation measured with the well-type chamber and the Farmer-in-Phantom system.

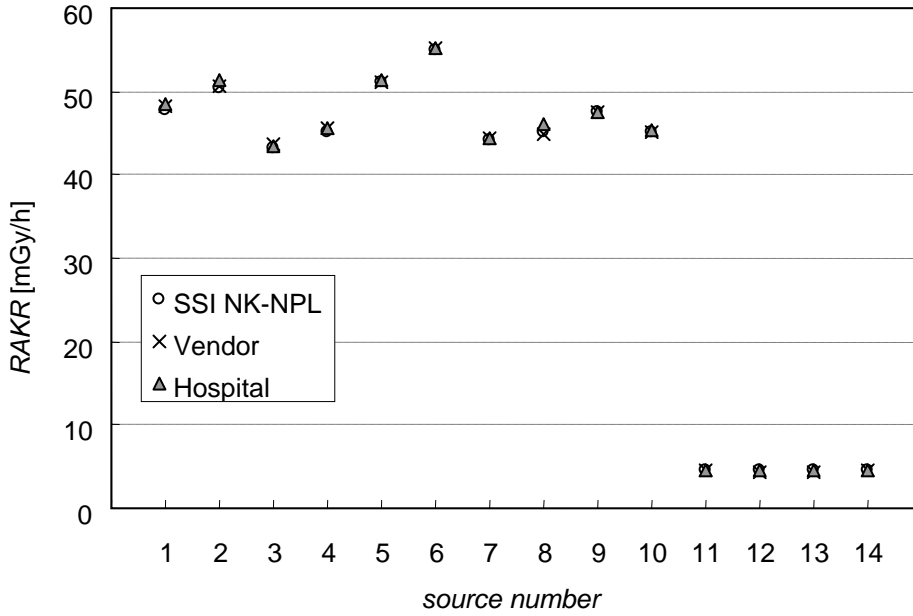
### 4.3 Estimation of uncertainty

The uncertainty in SSI's determination of the ionization current (corrected for influence quantities),  $I_{ion}$ , is  $\pm 0,2\%$  which leads to a total uncertainty in reference air-kerma rate,  $RAKR$ , of  $\pm 0,7\%$  (using the NPL calibration factor) at a coverage factor of  $k=1$ . This correspond to uncertainties of  $\pm 0,4\%$  and  $\pm 1,4\%$  respectively at a coverage factor of  $k=2$  (for details see the Appendix). The highest contribution to the total uncertainty in  $RAKR$  is contributed by the calibration factor. As determined here, the  $RAKR$  uncertainty disregards any contribution due to sources being of other design than the one used in the NPL calibration.

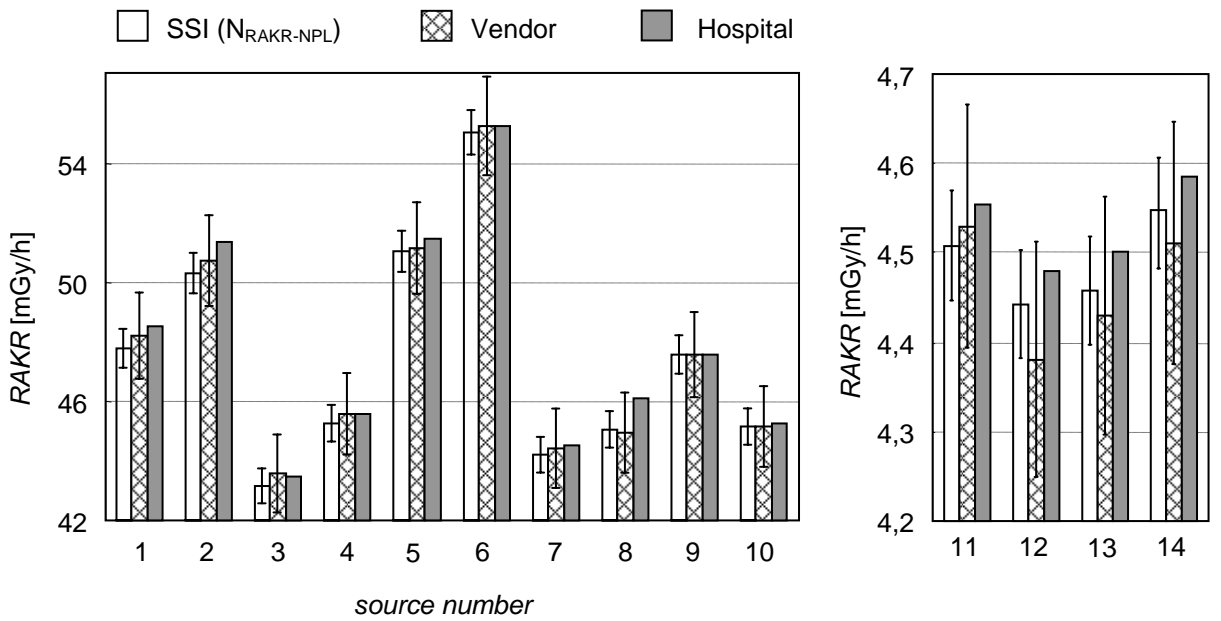
### 4.4 Audit results and discussion

Figure 9a shows the  $RAKR$  as measured by SSI, vendors and hospitals. The PDR-sources are recognized by being around ten times weaker. (All results are decay-corrected to the time stated on the vendor certificate. The fifth PDR-source was initially delivered and used for HDR purposes and therefore appears here as being of HDR-strength).

Figure 9b repeats the results of Figure 9a in more detail and also shows the uncertainty limits;  $\pm 3\%$  for vendors and  $\pm 1,4\%$  for SSI at a coverage factor of  $k=2$ . (Most vendors state an uncertainty in  $RAKR$  of  $\pm 5\%$  at a confidence limit of 99,7% which equals a coverage factor of  $k=3$  following GUM ((ISO, 1995)) and hence translates to  $\pm 3\%$  at  $k=2$ ).



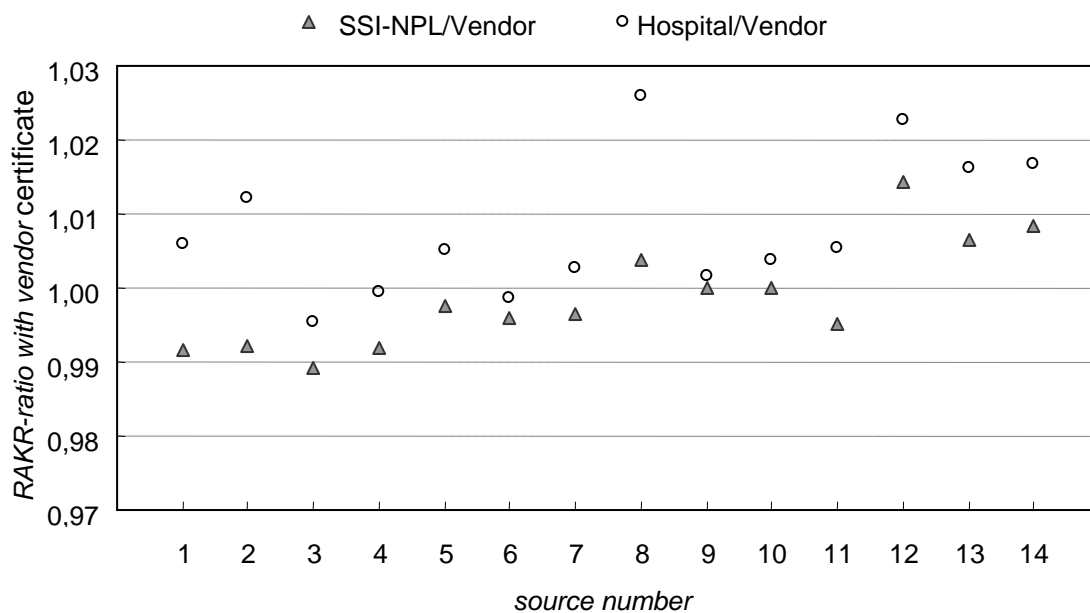
**Figure 9a** Values of  $RAKR$  for the sources as determined by SSI (using the calibration factor from NPL), vendors and hospitals. All source strengths refer to the date and time specified on the vendor's certificate.



**Figure 9b** Values of  $RAKR$  for the sources as measured by SSI (using the NPL calibration factor), vendors and hospitals. Uncertainty limits from SSI and vendors are inserted.

Figure 10 presents ratios of *RAKR* with vendor values as determined by SSI and hospitals, numbering the sources as in Figures 9a and 9b.

Both SSI and hospitals are in good agreement with vendors, the ratio of *RAKR*-values in all cases within the guaranteed uncertainty ( $\pm 3\%$  at  $k=2$ ). The uncertainty in vendor values has been reduced in the last years and the agreement seen in the Swedish audit is an improvement compared to what was seen in a similar investigations some 10 years ago (Venselaar *et al.*, (1994)). This is probably thanks to the development and use of well-type chambers designed for brachytherapy both at hospitals, vendor laboratories and SSDLs. Well-type chambers are more robust and far easier to setup than is the earlier commonly used free-in-air jigs equipped with Farmer-type chambers.

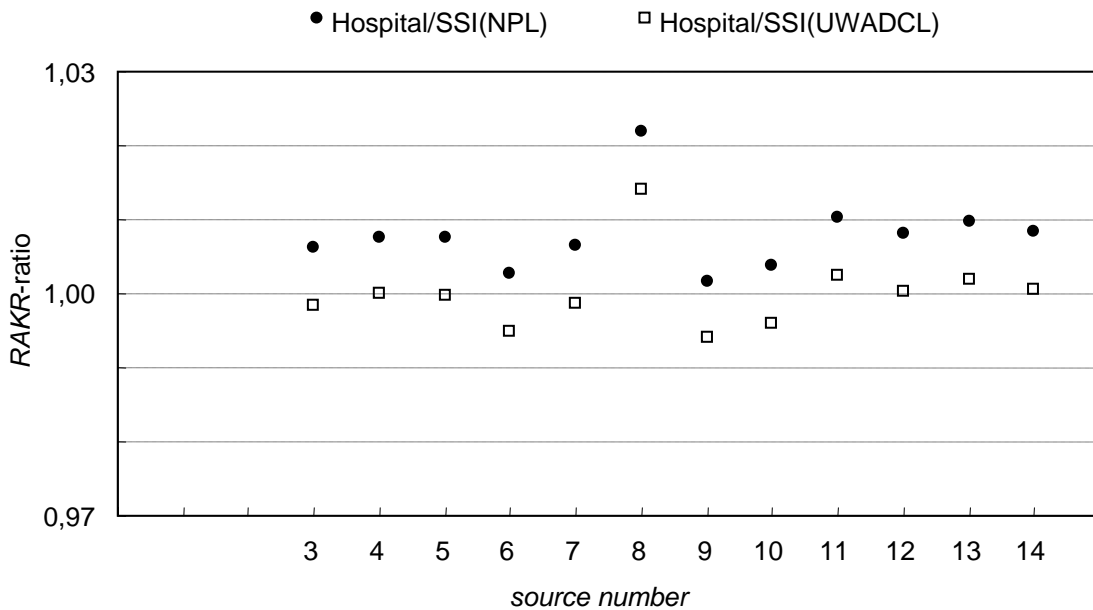


**Figure 10** Ratios of SSI- and hospital-determined *RAKR* to the same values on vendor certificates

For source number 8, the hospital's *RAKR* is 2,6% higher than the vendor's value. Although not outside the uncertainty limits it is a tendency not verified by the SSI (see also the hospital-ratio with SSI in Figure 11). The hospital holding source number 8 uses their chamber mounted on the wall in a corner of the room during measurements, without any corrections. An increased value could be expected, due to photons back-scattered from the walls towards the chamber. Studies on room-scatter as function of distance to the floor and walls for brachytherapy well-type ion chambers were performed by Podgorsak *et al.*, (1992). They show that it is worse to be close to a wall than close to the floor and say that even if corrections are applied, it is not advisable to place well-type chambers closer than 25 cm from a wall.

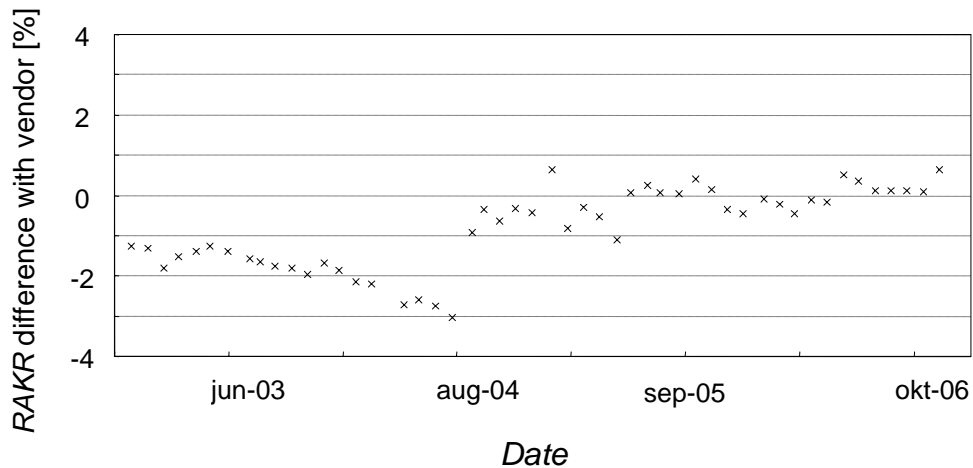
Embedded in ratios of *RAKR* are systematic differences due to traceability with different calibration laboratories. The hospital holding sources 1 and 2 uses their own interpolation technique for  $^{192}\text{Ir}$  calibrations (Drugge, (1995)) and is traceable to SSI through the inter-

polation quantities. The rest of the hospitals all have calibration factors from the UWADCL. Figure 11 shows values of *RAKR* from the UWADCL-traceable hospitals normalised to SSI-values obtained using either the SSI(NPL)- or the SSI(UWADCL)-calibration factors. Differences between hospitals and SSI using the SSI(UWADCL) calibration factor don't exceed  $\pm 0,6\%$ , excluding source number 8 (measured at the hospital with their well-chamber mounted on the wall). The hospital holding source number 8 uses their own value for verification purposes and enters that of the vendor in the treatment planning system. This means that if they stick to their geometry, the probable systematic error due to placement on the wall should be constant in time and embedded in their ratio with the source vendor.



**Figure 11** Comparing ratios of the hospitals RAKR determinations to those of SSI using either the NPL or the UWADCL calibration factors for the SSI well-chamber.

Figure 12 shows results from a Swedish hospital on their difference with vendor values for different HDR-sources within the same afterloading unit (reproduced with permission from Marie Lundell at the Karolinska Hospital in Stockholm). Having observed an increased deviation, the hospital contacted the vendor which resulted in that a problem with the pressure meter at the vendor's calibration laboratory was found and solved. Differences have since then been stable and within  $\pm 1\%$ . Figure 12 is an example of the usefulness of visualising results as function of time.



**Figure 12** The difference in estimated *RAKR* at a Swedish hospital relative to the vendor certificate for various HDR-sources within the same unit.

The establishment of a mean ratio (or mean difference) between the own hospital and the vendor for each afterloading unit is recommended. Such a ratio embeds the differences due to varying traceability as well as those due to source-type and setup. Provided that recommendations in equipment handling are followed (IAEA (2002)) and that measurements are performed in the same way each time (i.e. according to a written routine), the uncertainty in an established ratio has potential of being lower than that in *RAKR*. Most vendor certificates state an uncertainty in *RAKR* of  $\pm 3\%$  at  $k=2$ . Assuming an uncertainty in the calibration factor of  $\pm 2,5\%$  (the typical uncertainty at  $k=2$ , using the most common interpolation technique, see e.g. Table 1), this indicates an uncertainty of  $\pm 1\%$  in the ionization current (or charge) measurements at the vendor's laboratory (including all corrections for influence quantities etc. in these measurements). SSI estimates their uncertainty in current measurements to  $\pm 0,4\%$ , see the Appendix. Hospitals that follow recommendations on use of equipment can probably do as good as the vendors (who probably includes some safety margin) which would give an uncertainty in  $\pm 1,4\%$  for an established ratio. Variations in this ratio could be an early indicator on problems in some part of the system; either with the equipment or the measurement technique at the hospital or the vendor laboratory.

## 5. Conclusions

The accuracy in determining source strength for  $^{192}\text{Ir}$  brachytherapy is high at Swedish hospitals. All hospitals verify the strength of each new  $^{192}\text{Ir}$  source, using well-type chambers designed for brachytherapy. Values on source-strength measured by SSI and the hospitals all fell within the uncertainty limits guaranteed by the vendors.

The awaited start of a calibration service for  $^{192}\text{Ir}$  in Sweden will help solve the current problem of several hospitals having calibration factors that are too old according to international recommendations. Routines for verifying the constancy of the equipment and in setting it up for measurements varies and some hospitals could improve their routines. With the awaited start of a calibration service for  $^{192}\text{Ir}$  in Sweden, the hospitals will most

likely have to transport their chambers, a procedure that necessitates systems for constancy control of the equipment before and after transport. Hospitals without external  $^{60}\text{Co}$  beams can be recommended to purchase a  $^{137}\text{Cs}$  check-source for this purpose.

Hospitals can be recommended to establish their own ratio (or deviation) with the vendor and follow it as function of time. Such a mean-ratio embeds systematic differences of various origins and have a lower uncertainty than has the *RAKR* alone, making it useful for early detection of problems with equipment or routines.

There is room for SSI in advising hospitals regarding measurement techniques and maintenance of equipment, for instance by advising them to follow the IAEA recommendations. SSI could also define requirements for the agreement between source strengths as determined by hospitals and vendors. Such a recommendation could be coupled to an action plan, dependent on level of disagreement, and some kind of reporting to SSI.

## 6. Acknowledgement

Assistance from the physicists at the brachytherapy departments is greatly acknowledged. This project was funded by the Swedish Radiation Protection Authority (SSI project 1522.06).

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## Appendix - Estimation of uncertainty

The ionization current in the well-chamber, corrected for influence quantities,  $I_{ion}$ , is derived as:

$$I_{ion} = (I_{irr} - I_{leak}) \cdot k_T \cdot k_P \cdot e^{\frac{t \cdot \ln 2}{T_{1/2}}} \quad (A1)$$

where  $I_{irr}$  is the ionization current in the well-chamber during irradiation,  $I_{leak}$  is the leakage ionization current (obtained from the system in absence of irradiation),  $k_T$  and  $k_P$  are the correction factors for ambient temperature and pressure and  $e^{\frac{t \cdot \ln 2}{T_{1/2}}}$  is the correction for decay with  $T_{1/2}$  the half-life and  $t$  the time since the vendor-issued calibration.

The experimental determination of the reference air-kerma rate,  $RAKR$ , of the sources is derived as:

$$RAKR = N_{RAKR} \cdot I_{ion} \quad (A2)$$

where  $N_{RAKR}$  is the calibration factor of the well-chamber

The uncertainty in  $I_{ion}$  and  $RAKR$  is derived as the combined uncertainty of the individual input components in Eqs. A(1)-A(2), following recommendations in the GUM-report ((ISO, 1995) and assuming the inputs to be uncorrelated. Details on the uncertainty of the individual inputs are given below. The relative uncertainty in  $I_{ion}$  was determined to 0,2% and in  $RAKR$  to 0,7% at a coverage factor of 1, which corresponds to 0,4% and 1,4% respectively at a coverage factor of 2. This estimation of uncertainty is without accounting for possible effects due to differences in sources design and hence strictly valid only for measurements of a MicroSelectron classic HDR source from Nucletron BV, as used in the NPL-calibration. The uncertainty for measuring sources of other design is not known in detail. For HDR -sources having an active length of the  $^{192}\text{Ir}$  material similar to that of the Microselectron Classic differences were less than the uncertainty in calibration factors and could therefore not be resolved, see Stump *et al.* (2002).

### Uncertainties in the individual inputs

The uncertainties of the various factors of Eq. (A1) are derived below, at a coverage factor of one.

#### Uncertainty in $N_{RAKR}$

The uncertainty in the calibration factor is obtained with the calibration factor from the calibration certificate issued by the calibration laboratory. The uncertainty in the calibration factor from NPL,  $\sigma_{N_{RAKR-NPL}}$ , is 1,3% at a coverage factor of 2 and hence 0,65% at a coverage factor of 1.

<b>Contribution</b>	<b>Method for estimation</b>
Uncertainty in $N_{RAKR}$ -NPL	From calibration certificate
Combined	0,65%

### Uncertainty in $I_{irr}$

<b>Contribution</b>	<b>Method for estimation</b>	<b>Type A 1s [%]</b>	<b>Type B 1s [%]</b>
Positioning of source	Standard deviation in signal from 3 repeated insertions	0,005	
Current reading	Standard deviation of the mean in manual current readings from electrometer  (The mean of 10-15 current readings are used as the signal value)	0,0025 (HDR) or 0,01 (PDR)	
Setup	Standard deviation in repeated setups for one source	0,05	
Maximum response curve	Measurements at maximum 5mm from point of maximum response of well-chamber	0,02	
Calibrating e-m against "App 1"	Standard deviation in repeated calibrations of electrometer against "App 1" at SSI	0,05	
Recombination	The uncertainty in factor (derived with two-voltage method) assumed of similar magnitude as the correction.		0,1
Uncertainty in "App 1"	From Jan-Erik Grindborg, SSI	0,05	
Stability	Standard deviation in constancy checks	0,1	
<b>Combined; HDR</b>	0,17 %		
<b>Combined; PDR</b>	0,17 %		

"App 1" is SSI's calibrated reference electrometer. The standard deviation in current readings are somewhat higher for the weaker PDR-sources, however, the difference is not significant for the combined uncertainty which is dominated by the stability.

### Uncertainty in $I_{leak}$

<b>Contribution</b>	<b>Method for estimation</b>	<b>Type A 1s [%]</b>	<b>Type B 1s [%]</b>
Current reading	Standard deviation in manual current readings	0,05	
Calibrating e-m against “App 1”	Standard deviation in repeated calibrations against App 1 at SSI	0,05	
Uncertainty in App 1	From Jan-Erik Grindborg, SSI	0,05	
Stability	Standard deviation in constancy checks	0,1	
<b>Combined</b>	0,132 %		

### Uncertainty in $k_T$

The signal is corrected for ambient temperature according to:

$$k_T = \frac{T}{293,15} + \frac{273,15}{293,15}$$

where  $T$  is the temperature in degrees Celsius. Below is the uncertainty in the temperature  $T$  derived.

<b>Contribution</b>	<b>Method for estimation</b>	<b>Type A 1s [%]</b>	<b>Type B 1s [%]</b>
Calibration against SSI-reference	Standard deviation in the correction from multiple comparisons of field and reference instruments, converted to uncertainty in T	0,25	
Uncertainty in reading instrument	One decimal resolution yields uncertainty of 0,05 degrees		0,25
Uncertainty in reference instrument	From Jan-Erik Grindborg, SSI	0,005	0,006
<b>Combined</b>	0,35 %	0,35	0,006

An uncertainty in  $T$  of 0,35% amounts to an uncertainty in  $k_T$  of 0,02%.

### Uncertainty in $k_p$

The signal is corrected for ambient pressure according to:

$$k_p = \frac{101,325}{P}$$

where  $P$  is the pressure in kPa. Below is the uncertainty in the pressure  $P$  derived.

Contribution	Method for estimation	Type A 1s [%]	Type B 1s [%]
Calibration against SSI-reference	Standard deviation in the correction from multiple comparisons of field and reference instruments, converted to uncertainty in P	0,12	
Uncertainty in reading of instrument	From resolution of analog instrument		0,05
Uncertainty in ref instrument	From Jan-Erik Grindborg, SSI	0,007	0,002
<b>Combined</b>	0,13%		

An uncertainty in  $P$  of 0,13% amounts to an uncertainty in  $k_p$  of 0,13%.

### Uncertainty in $e^{-\frac{t \ln 2}{T_{1/2}}}$

The uncertainty in the decay correction arising from an uncertainty in the time of measurement between current measurement and that made at the vendor laboratory is considered. Any uncertainty in the half time of decay is negligible.

Contribution	Method for estimation	Type A 1s [%]	Type B 1s [%]
Error in time of measurement specified by date:hour:minute	Errors in time of the experimentalists watch relative that of the vendor laboratory: 5 minutes. Shortest period between the vendor calibration and measurement: 10 days		0,04
<b>Combined</b>			

An uncertainty in  $t$  of 0,04 % amounts to an uncertainty in the decay correction of  $e^{-\frac{t \ln 2}{T_{1/2}}}$  of 0,005%.

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