

MAY NOT BE SAME AS THE PUBLISHED VERSION

**CCRI supplementary comparison of standards for
absorbed dose to water in ^{60}Co gamma radiation
at radiation processing dose levels**

D.T. Burns^{a,*}, P.J. Allisy-Roberts^a, M.F. Desrosiers^b, V. Yu. Nagy^b, P.H.G. Sharpe^c,
R.F. Laitano^d, K. Mehta^e, M.K.H. Schneider^f, Y. Zhang^g

^a*Bureau International des Poids et Mesures, Pavillon de Breteuil, F- 92312 Sèvres Cedex*

^b*National Institute of Standards and Technology, Gaithersburg, MD, USA*

^c*National Physical Laboratory, Teddington, Middlesex, UK*

^d*Istituto Nazionale di Metrologia delle Radiazioni Ionizzanti, Rome, Italy*

^e*International Atomic Energy Agency, Vienna*

^f*Physikalisch-Technische Bundesanstalt, Braunschweig, Germany*

^g*National Institute of Metrology, Beijing, China*

Abstract

Six national standards for absorbed dose to water in ^{60}Co gamma radiation at the dose levels used in radiation processing have been compared over the range from 5 kGy to 30 kGy using the alanine dosimeters of the NIST and the NPL as the transfer dosimeters. The standards are in agreement at the level of around 0.5 %, which is significantly smaller than the stated standard uncertainties..

Keywords: alanine ,calibration, comparison, dosimetry, gamma radiation, standards

1. Introduction

At its meeting in July 1997, the Consultative Committee for Ionizing Radiation (CCRI), Section I (for x- and gamma-rays and electrons), proposed a comparison of the high-dose standards for absorbed dose to water in ^{60}Co gamma radiation among the primary dosimetry laboratories operating standards and services in this field. The comparison would be organized by the Bureau International des Poids et Mesures (BIPM) and would complement an earlier CCRI comparison organized by the International Atomic Energy Agency (IAEA) in collaboration with the BIPM (IAEA, 1995). In particular, the new comparison would involve a more robust transfer dosimeter with a view to reducing the uncertainties. In the framework of the Mutual Recognition Arrangement of the International Committee for Weights and Measures (CIPM MRA) (BIPM, 1999), the comparison is classed as a supplementary comparison, with reference CCRI(I)-S1, and as such the present report will be referenced in the BIPM key comparison database (KCDB).

Six institutes offering a high-dose irradiation service took part in the present comparison; the Istituto Nazionale di Metrologia delle Radiazioni Ionizzanti (ENEA-INMRI, Italy), the National Institute of Metrology (NIM, China), the National Institute of Standards and Technology (NIST, USA), the National Physical Laboratory (NPL, UK), the Physikalisch-Technische Bundesanstalt (PTB, Germany) and the IAEA (Vienna). In addition, the BIPM, although it does not offer a

* Corresponding author. Fax +33 1 4534 2021
Email address: dburns@bipm.org

high-dose service, took part at a lower dose level (1 kGy) to provide a direct link to the international reference for absorbed dose to water in ^{60}Co . To render the comparison more robust, two transfer dosimeters were selected for the comparison; the alanine / ESR dosimetry system of the NIST (Humphries et al., 1998) and that of the NPL (Sharpe and Sephton, 2000) (the previous CCRI comparison was conducted using the IAEA alanine as the transfer dosimeter).

2. High-dose standards and transfer dosimeters

For each of the seven participating institutes, the basis of the ^{60}Co standard for absorbed dose to water and the means of transfer of the dosimetry to an industrial irradiator are summarized in Table 1. Also given in the table is the combined relative standard uncertainty u_i of the mean absorbed dose to water, $D_{w,i}$, over the dimension of each alanine transfer dosimeter, as estimated by each irradiating institute.

The NIST alanine dosimeters for use in ^{60}Co are supplied in watertight cylindrical holders nominally 12 mm in diameter and 29 mm in length. The stated relative standard uncertainty of dose estimates derived using the NIST dosimeters is 1.1 %. The NPL alanine dosimeters are also supplied in cylindrical holders, nominally 12 mm in diameter and 17 mm in length; these are not normally watertight but may be made so if requested. The stated relative standard uncertainty of dose estimates derived using the NPL dosimeters is also 1.1 %. Over the temperature range of the comparison, both the NIST dosimeter (Nagy et al., 2000) and the NPL dosimeter have a temperature coefficient of approximately 0.15 % per K.

Table 1

Basis of estimates of absorbed dose to water at the various institutes at the time of the comparison.

Institute	Standard of absorbed dose to water in ^{60}Co reference field	Transfer to high-dose irradiator	u_i / %	Reference
BIPM	Primary standard ionization chamber	- ^a	0.4	Boutillon and Perroche, 1993
ENEA	Graphite calorimeter + scaling theorem	Dichromate dosimeter via Fricke dosimeter in calibration irradiator	1.5	Guerra et al., 1996; Laitano 1999
IAEA	Secondary standard ionization chamber ^b	NPL dichromate dosimeter	1.2	Mehta and Girzikowsky, 1999
NIM	Fricke dosimeter	- ^a	1.5	Zong Yuda et al., 1998
NIST	Water calorimeter	Alanine dosimeter	0.9	Humphries et al., 1998
NPL	Graphite calorimeter + scaling theorem	Fricke dosimeter	1.1	Burns, 1994; Sharpe and Burns, 1995
PTB	Total absorption in Fricke dosimeter	Fricke dosimeter	1.5 / 1.0 ^c	Feist, 1982; Schneider, 2002

^a No irradiator employed; alanine transfer dosimeters irradiated directly in ^{60}Co reference field.

^b The IAEA is traceable to the BIPM.

^c First figure refers to irradiation of NIST alanine, second to NPL alanine (difference due to dosimeter sizes).

3. Comparison procedure

A protocol for the comparison was issued by the BIPM in May 1998. Each irradiating institute (other than the BIPM) was sent, in late August 1998, fourteen alanine transfer dosimeters from the NIST and fourteen from the NPL. Of each fourteen, two remained unirradiated (as control dosimeters) and four were irradiated to each of three nominal dose levels; 5 kGy, 15 kGy¹ and 30 kGy. Irradiations at all institutes took place in the two-week period beginning 7 September 1998². The dosimeters were returned immediately to the issuing institutes with information on irradiation temperatures but no information on dose estimates. By January 1999, all irradiating laboratories and both issuing laboratories had sent their dose estimates to the BIPM for analysis, along with an information sheet giving details of the basis of the dose estimates. However, documentation of the standards and particularly their uncertainty budgets were not available for all institutes until some time later.

¹ The ENEA irradiated to a dose level of 10 kGy instead of 15 kGy.

² The IAEA was unable to irradiate the NIST dosimeters because of a small difference between the nominal size of the alanine dosimeter holder and its actual size.

Unlike the other institutes, the BIPM does not maintain a high-dose irradiation field and was included in the comparison principally as the co-ordinator. Nevertheless the BIPM holds a primary standard for absorbed dose to water in ^{60}Co gamma radiation at radiotherapy levels and therefore also took part in the irradiations, following the same protocol except that only one dose level (1 kGy) was practicable because of the very low dose rate (0.013 kGy h^{-1}). In order to sustain the ‘blind’ nature of the present comparison, the irradiations at the BIPM were performed independently of the person responsible for the analysis of the data from all institutes.

The irradiation geometry was not specified in detail in the protocol, but rather it was preferred that each irradiating institute use their normal arrangement. This policy was adopted in order that the dose estimates be representative of those routinely disseminated by each institute, rather than modified for the purpose of the present comparison. All institutes other than the NIM and the BIPM employed a laboratory-scale self-shielded irradiator. The NIM and the BIPM irradiated the alanine dosimeters in a water phantom under their reference conditions in ^{60}Co .

4. Results and discussion

The results using the NIST alanine transfer dosimeters are given in Table 2. In this table, $R_{i,\text{NIST}}$ is the mean value, for each institute and at each dose level, of the four values for R_{dosim} , where

$$R_{\text{dosim}} = D_{w,i} / D_{w,\text{alan}}. \quad (1)$$

Here, $D_{w,i}$ is the mean absorbed dose to water over the dimension of each transfer dosimeter as estimated by the irradiating institute i , and $D_{w,\text{alan}}$ is the same quantity as estimated by the NIST using their alanine dosimeter. Also given in the table is the statistical standard uncertainty $s_{i,\text{NIST}}$ of $R_{i,\text{NIST}}$.

The results for $R_{i,\text{NIST}}$ are shown in Figure 1. The uncertainty bars represent the statistical standard uncertainty $s_{i,\text{NIST}}$ only. For each of the three dose levels, the relative standard deviation of the four results for $R_{i,\text{NIST}}$ is 0.5 %. Recalling the values for the standard uncertainty u_i given in Table 1, the results for $R_{i,\text{NIST}}$ for each dose level show agreement between the institutes at a level that is well within one standard uncertainty u_i for each institute.

The results using the NPL alanine are given in Table 3 and Figure 2. The relative standard deviation of the five results for $R_{i,\text{NPL}}$ at each dose level is 1.1 %. However, it is evident from both figures that the NIST dose estimates are relatively high. Removing the NIST results from Figure 2 reduces the relative standard deviation to 0.5 %, 0.6 % and 1.0 % for the three dose levels 5 kGy, 15 kGy and 30 kGy, respectively. Again, the values for 5 kGy and 15 kGy are lower than one would expect from the standard uncertainties u_i given in Table 1 and may indicate that some uncertainty components have been overestimated.

The result for the BIPM at 1 kGy relative to the NPL alanine is consistent at the 0.2 % level with the results of international comparisons of reference absorbed dose to water in ^{60}Co . For the BIPM relative to the NIST the difference from the international comparison result is around 0.7 %, which is within the stated uncertainty u_i of Table 1.

It is also of note that the standard deviation of the results at each dose level is significantly smaller than the values in excess of 2 % observed in the previous high-dose comparison (IAEA, 1995).

The data demonstrate that the NIST alanine dose estimates are higher than the NPL alanine estimates. This has been seen previously in validation comparisons conducted between the two institutes (Desrosiers and Sharpe, private communication). The best estimate of the ratio

$D_{w,NIST} / D_{w,NPL}$ for each dose level is evaluated from the present data by taking the weighted mean of the five estimates derived from the $R_{i,NIST}$ and $R_{i,NPL}$ values for the ENEA, NIM, PTB, NIST and the NPL (the IAEA did not irradiate the NIST dosimeters and the BIPM did not use a comparable dose level). For this purpose, only the statistical uncertainties $s_{i,NIST}$ and $s_{i,NPL}$ have been used for the weighting. The values for $D_{w,NIST} / D_{w,NPL}$ so derived are 1.019 (statistical uncertainty 0.002) for the 5 kGy and 15 kGy dose levels and 1.010 (0.003) for the 30 kGy dose level. Although measurable within the statistical uncertainties, these differences in dose estimates are within the combined standard uncertainty (0.016).

Following the present comparison, a NIST internal re-evaluation of its calibration service dose rates was facilitated by improvements to the detector technology and the experimental design (Desrosiers and Puhl, 2001). This resulted in a decrease of 1.8 % in the NIST dose estimates for the particular arrangement used for the present comparison, in good agreement with the ratio $D_{w,NIST} / D_{w,NPL}$ observed in the present work.

5. Registration in the KCDB

In the framework of the CIPM MRA, this comparison is registered as the supplementary comparison CCRI(I)-S1. Although no degrees of equivalence are registered for supplementary comparisons, the present report will be referenced in Appendix B of the KCDB. In order that the results be representative of each institute's present ability to disseminate absorbed dose at high-dose levels, the following analysis uses dose estimates $D_{w,alan}$ for the NIST alanine that are reduced by 1.8 % from those used to evaluate $R_{i,NIST}$ in Table 2 and a similar reduction of the estimates $D_{w,i}$ used to evaluate $R_{i,NPL}$ for the NIST in Table 3.

Although the use of two transfer dosimeter systems is more robust, only one result is permitted for each institute at each dose level and so the two sets of data $R_{i,NIST}$ and $R_{i,NPL}$ have been combined. To this end, the best estimate of the ratio $D_{w,NIST} / D_{w,NPL}$ evaluated above (for each dose level) has been used to relate the results $R_{i,NIST}$ and $R_{i,NPL}$ obtained for the ENEA, the NIM and the PTB. A similar procedure has been used for the NPL irradiation of the NIST alanine and for the NIST irradiation of the NPL alanine. Furthermore, the value $R_{i,NIST} = 1$ has been included (at each dose level) for the NIST in the data of Table 2 and Figure 1, since the horizontal line in the figure represents valid NIST dose estimates that should not be lost from the analysis. Similarly for the NPL (Table 3 and Figure 2).

In this way, two values are obtained (at each dose level) for each of the ENEA, NIM, PTB, NIST and the NPL and the arithmetic mean of each pair is taken. Note that only one estimate exists for the IAEA and that the BIPM data are not included in this analysis since no high-dose standard is maintained at the BIPM.

Thus a single set of values is obtained (at each dose level) that represents the combined data. In the final stage of the analysis, these values are re-normalized to give a set of values R_i (at each dose level) such that the arithmetic mean value R_{mean} is unity, and the set of differences $x_i = (R_i - R_{mean})$ is evaluated. The standard uncertainty $u_{R,i}$ of each R_i is taken to be the corresponding u_i of Table 1 combined with the small uncertainty arising in the above analysis from the statistical uncertainties $s_{i,NIST}$ and $s_{i,NPL}$. The standard uncertainty $u_{R,mean}$ of R_{mean} is taken as the statistical standard uncertainty of the mean of the R_i . This is considered to be appropriate because the standards are almost completely uncorrelated.

The results for the differences x_i and the standard uncertainties $u_{x,i}$ are given in Table 4.

6. Conclusions

The evaluation of the differences x_i in Section 5 reduces the results for each institute to a single value for each dose level. The statistical standard uncertainty of the distribution of the x_i therefore represents the general level of agreement between the institutes. The values obtained are 0.4 % for the 5 kGy and 15 kGy dose levels and 0.6 % for the 30 kGy level. These results demonstrate that the high-dose standards are in agreement at a level that is well within the standard uncertainty u_i for each institute, as given in Table 1. It should be noted, however, that this level of agreement was obtained following the change to the NIST dose estimates noted in Section 4.

References³

- CIPM, 1999. Mutual recognition of national measurements standards and of measurement certificates issued by national metrology institutes. Bureau International des Poids et Mesures, Sèvres.
- Boutillon, M., Perroche, A.-M., 1993. Ionometric determination of absorbed dose to water for cobalt-60 gamma rays. *Phys. Med. Biol.* 38, 439–454.
- Burns, J.E., 1994 Absorbed-dose calibrations in high-energy photon beams at the National Physical Laboratory : conversion procedure. *Phys. Med. Biol.* 39, 1555–1575.
- Desrosiers, M.F., Puhl, J.C., 2001. NIST ⁶⁰Co radiation-processing calibration fields. CCRI(I)/01-16, Bureau International des Poids et Mesures, Sèvres.
- Guerra, A.S., Laitano, R.F., Pimpinella, M., 1996. Characteristics of the absorbed-dose-to-water standard at ENEA. *Phys. Med. Biol.* 41, 657–674.
- Feist, H., 1982. Determination of the absorbed dose to water for high-energy photons and electrons by total absorption of electrons in ferrous sulphate solution. *Phys. Med. Biol.*, 27, 1435–1447.
- Humphries, J.C., Puhl, J.M., Seltzer, S.M., McLaughlin, W.L., Desrosiers, M.F., Bensen, D.L., Walker, M.L., 1998. Radiation processing dosimetry calibration services and measurement assurance program. NIST special publication 250–44. National Institute of Standards and Technology, Gathersburg, MD.
- IAEA, 1995. High-dose intercomparison in the ⁶⁰Co field - Report of the IAEA to the CCEMRI Section I. CCEMRI(I)/95-15, Bureau International des Poids et Mesures, Sèvres.
- Laitano, R.F., 1999. Dosimetry standards at the ENEA-INMRI. CCRI(I)/99-21, Bureau International des Poids et Mesures, Sèvres.
- Mehta, K., Girzikowsky R., 1999. IAEA reference dosimeter: Alanine-ESR. Proceedings of a symposium on techniques for high-dose dosimetry in industry, agriculture and medicine (Vienna, 2-5 November 1998). IAEA-SM-356/63. International Atomic Energy Agency, Vienna, 299–304.
- Nagy, V.Yu., Puhl, J.M., Desrosiers, M.F., 2000. Advancements in Accuracy of the Alanine Dosimetry System. Part 2. The Influence of the Irradiation Temperature. *Radiat. Phys. Chem.* 57, 1–9.
- Schneider, M.K.H., 2002. Die Gammacell-Eine Bestrahlungsanlage für hohe Dosen und Dosisleistungen. PTB-Berichte der Serie Dos (Dosimetrie) Dos-42, ISBN 3-89701-912-4.
- Sharpe, P. H. G. and Burns, D.T., 1995. The relative response of Fricke, dichromate and alanine dosimeters to Co-60 and high energy electron beam radiation. *Radiat. Phys. Chem.* 46, 1273–1277.
- Sharpe, P., Sephton, J., 2000. An automated system for the measurement of alanine/EPR dosimeters. *Appl. Radiat. Isot.* 52, 1185–1188.

³ CCRI documents from 2001 onwards are available on the BIPM website (www.bipm.org). Older BIPM references (including CCRI and CCEMRI reports) are available on request from the BIPM or from the corresponding author (dburns@bipm.org).

Zong Yuda, Zhang Yanli, Gao Juncheng, Liu Zhimian, Xia Xuan, Li Chenghua, Xie Liqing, 1998. Calorimeters for absorbed dose standard of electron beam radiation processing. Radiat. Phys. Chem. 53, 549–553.

Figure captions

Figure 1. Results for the comparison ratios $R_{i,NIST}$ using the alanine transfer dosimeter of the NIST. The uncertainty bars represent the statistical standard uncertainty $s_{i,NIST}$.

Figure 2. Results for the comparison ratios $R_{i,NPL}$ using the alanine transfer dosimeter of the NPL. The uncertainty bars represent the statistical standard uncertainty $s_{i,NPL}$.

Table 2
Absorbed-dose estimates for irradiations
involving the NIST transfer dosimeters.

Institute	Dose level / kGy	$R_{i,NIST}$	$s_{i,NIST}$
ENEA	5	0.9798	0.0020
	10	0.9784	0.0014
	30	0.9923	0.0024
NIM	5	0.9802	0.0029
	15	0.9830	0.0038
	30	0.9981	0.0031
NPL	5	0.9794	0.0022
	15	0.9736	0.0026
	30	0.9896	0.0011
PTB	5	0.9693	0.0017
	15	0.9715	0.0016
	30	0.9858	0.0020
BIPM	1	0.9949	0.0017

Table 3
 Absorbed-dose estimates for irradiations
 involving the NPL transfer dosimeters.

Institute	Dose level / kGy	$R_{i,NPL}$	$S_{i,NPL}$
ENEA	5	0.9915	0.0029
	10	0.9899	0.0028
	30	0.9875	0.0018
NIM	5	0.9971	0.0024
	15	1.0027	0.0014
	30	1.0113	0.0051
NIST	5	1.0181	0.0025
	15	1.0169	0.0021
	30	1.0139	0.0021
PTB	5	0.9896	0.0023
	15	0.9921	0.0023
	30	0.9960	0.0017
IAEA	5	1.0004	0.0018
	15	0.9991	0.0020
	30	1.0040	0.0029
BIPM	1	1.0029	0.0014

Table 4

Results at each dose level for the difference $x_i = (R_i - R_{\text{mean}})$, where R_i is the combined comparison result for institute i and $R_{\text{mean}} = 1$, and the combined standard uncertainty $u_{x,i}$ of this difference. These results are obtained following adjustment of the NIST dose estimates as noted in Section 4.

	Dose level					
	5 kGy		15 kGy		30 kGy	
Institute	x_i	$u_{x,i}$	x_i	$u_{x,i}$	x_i	$u_{x,i}$
ENEA	-0.002	0.015	-0.004	0.015	-0.005	0.015
IAEA	0.003	0.012	0.002	0.012	0.004	0.013
NIM	0.001	0.015	0.005	0.015	0.010	0.016
NIST	0.004	0.010	0.003	0.010	-0.006	0.011
NPL	0.002	0.011	-0.001	0.011	0.000	0.011
PTB	-0.008	0.013	-0.006	0.013	-0.004	0.013

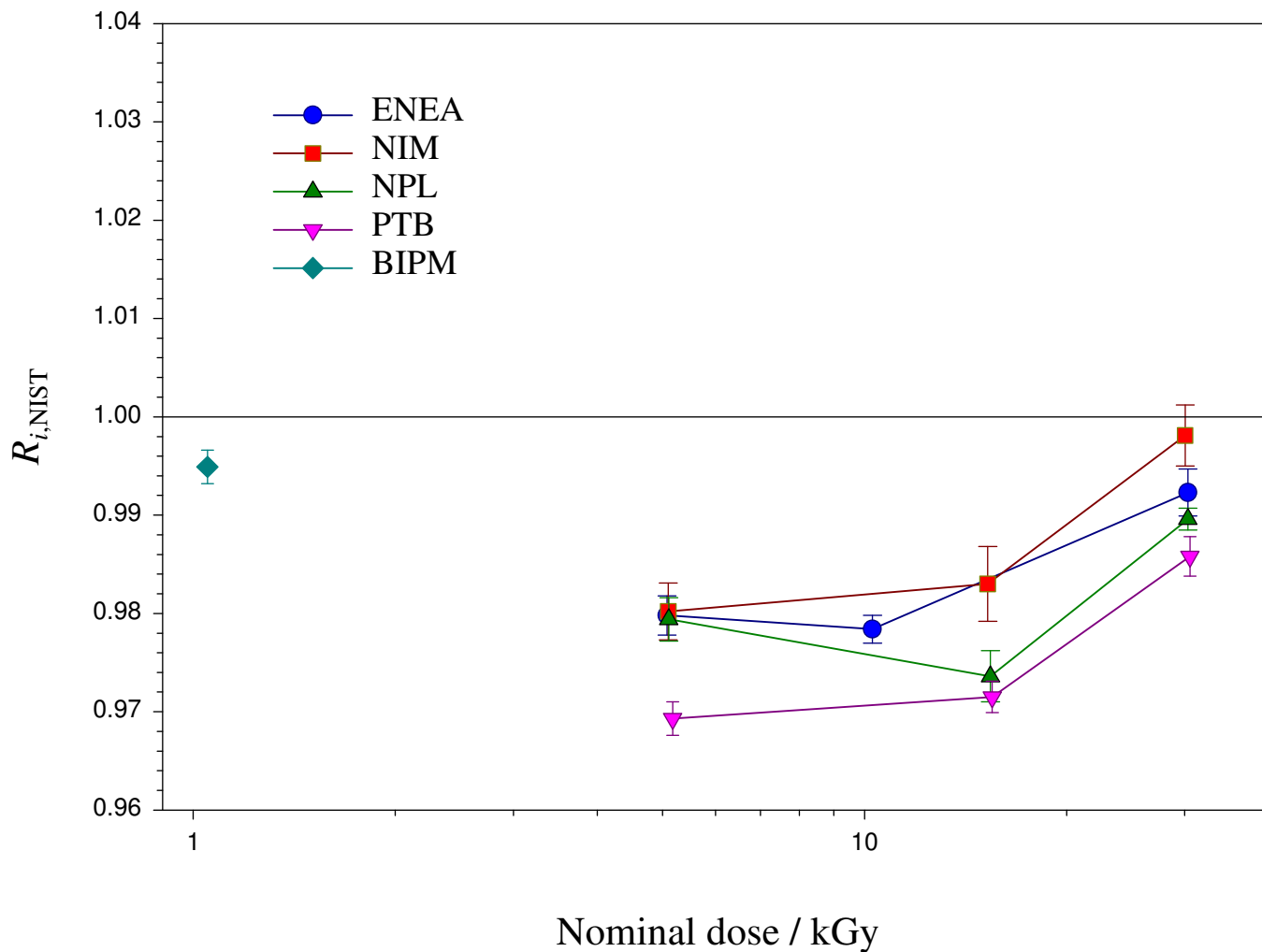


Figure 1. Results for the comparison ratios $R_{i,NIST}$ using the alanine transfer dosimeter of the NIST. The uncertainty bars represent the statistical standard uncertainty $s_{i,NIST}$.

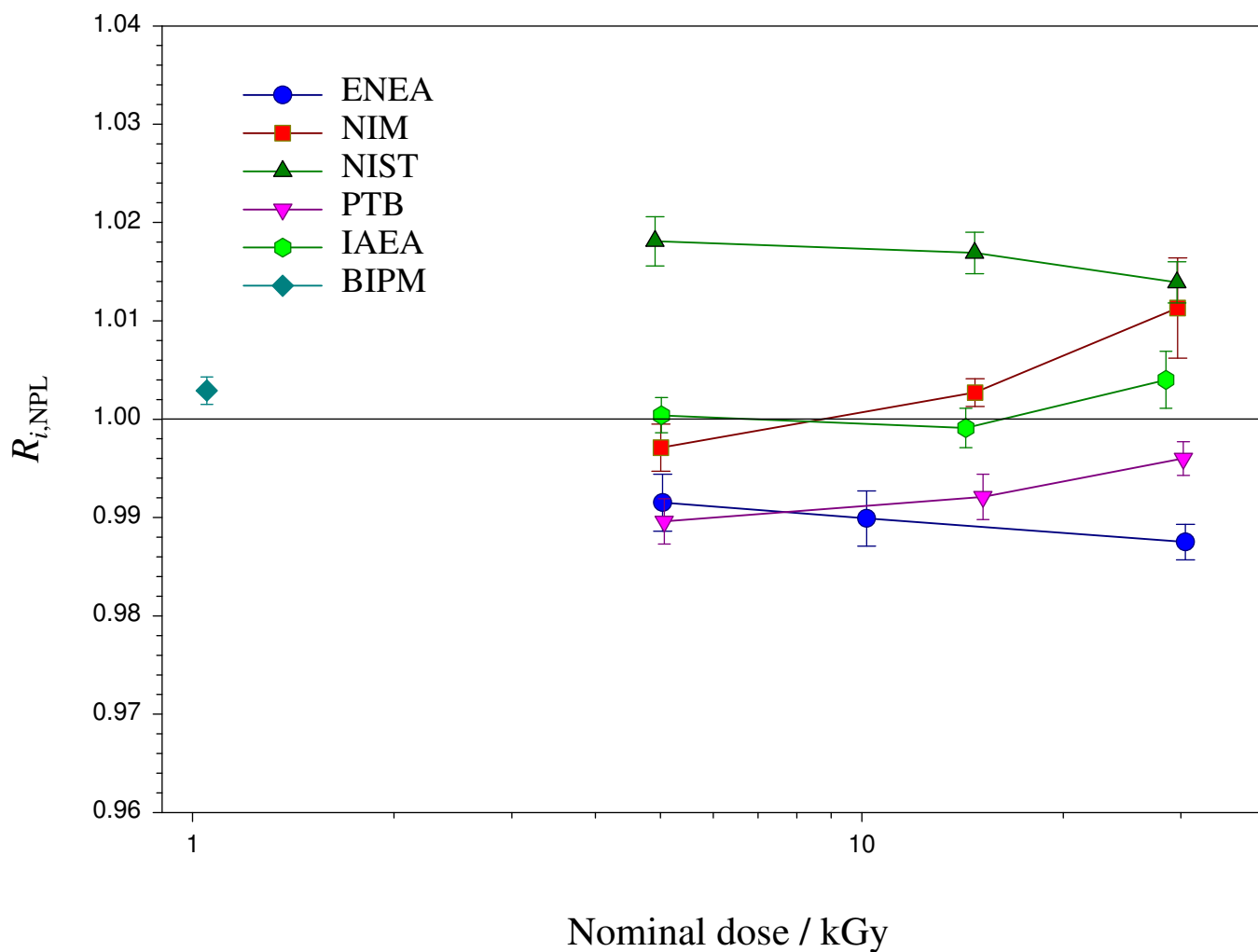


Figure 2. Results for the comparison ratios $R_{i,NPL}$ using the alanine transfer dosimeter of the NPL. The uncertainty bars represent the statistical standard uncertainty $s_{i,NPL}$.