

Short communication

## A note on reporting radiocarbon

J. van der Plicht<sup>a,b,\*</sup>, A. Hogg<sup>c</sup>

<sup>a</sup>Center for Isotope Research, Groningen University, Groningen, Netherlands

<sup>b</sup>Faculty of Archaeology, Leiden University, Leiden, Netherlands

<sup>c</sup>Radiocarbon Dating Laboratory, University of Waikato, Hamilton, New Zealand

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### Abstract

Recommended reporting practice concerning <sup>14</sup>C dates, relevant for Quaternary Geochronology, is given in this report.  
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Reporting practice of <sup>14</sup>C dates can be found in an original publication of [Stuiver and Polach \(1977\)](#). This work has been extended and corrected later by [Mook and van der Plicht \(1999\)](#). In the latter publication, several new “rational” symbols were introduced, in an attempt to end confusion that developed over time. For an in-depth treatise we refer to these two seminal publications. Here we summarize the <sup>14</sup>C practice most relevant for the Quaternary Sciences.

First we introduce the <sup>14</sup>C activity ratio <sup>14</sup>*a*. This is defined as the <sup>14</sup>C concentration in the sample material, relative to the <sup>14</sup>C concentration or <sup>14</sup>C activity in the reference material:

$${}^{14}a = \frac{{}^{14}A[\text{sample}]}{{}^{14}A[\text{reference}]} \quad (1)$$

Hence the <sup>14</sup>*a* value ranges between 0 (background or infinite age) and 1 (modern value), or equivalently 0% and 100%. This is equivalent to pM or pMC (percent Modern Carbon), which is an ambiguous expression—see [Mook and van der Plicht \(1999\)](#).

\*Corresponding author. Center for Isotope Research, Groningen University, Groningen, Netherlands. Tel.: +31 50 3634730; fax: +31 50 3634738.

E-mail address: [j.van.der.plicht@rug.nl](mailto:j.van.der.plicht@rug.nl) (J. van der Plicht).

The relative <sup>14</sup>C content is defined as

$${}^{14}\delta = {}^{14}a - 1 \quad (2)$$

which is expressed in per mill (‰) deviation from the reference. This is analogous to stable isotope practice (<sup>13</sup>δ, <sup>18</sup>δ, etc).

The reference material has a <sup>14</sup>C activity of 13.56 dpm/gC or 0.226 Bq/gC. It is based on 95% of the value of the specific activity of the original NBS (now NIST) oxalic acid (HOx1) in the year AD 1950 ([Karlén et al., 1966](#)). A secondary oxalic acid standard (HOx2) is now in common use in most <sup>14</sup>C laboratories. It has a defined activity ratio compared with the Ox1 standard of  $1.2933 \pm 0.001$  ([Mann, 1983](#)).

For the stable isotope <sup>13</sup>C, the reference is VPDB ([Gonfiantini, 1984](#)).

Mass dependent processes in nature and in the laboratory can cause isotopic fractionation. For <sup>14</sup>C measurements, this changes the <sup>14</sup>C content in samples producing errors in <sup>14</sup>C ages if not corrected for. Since fractionation occurs to both <sup>13</sup>C and <sup>14</sup>C and because the relationship between the fractionation for <sup>13</sup>C and <sup>14</sup>C is known, the <sup>13</sup>δ value of the sample material to be dated can be used for fractionation correction.

It has become common practice to normalize <sup>14</sup>C results for deviations of the measured <sup>13</sup>δ from −25‰.

The  $^{14}\text{C}$  activity and relative content, as defined above, therefore need to be corrected for isotopic fractionation by normalizing (subscript  $N$ ) to  $^{13}\delta_N = -25\%$ :

$$^{14}a_N = ^{14}a \left[ \frac{1 + ^{13}\delta_N}{1 + ^{13}\delta} \right]^2 = ^{14}a \left[ \frac{0.975}{1 + ^{13}\delta} \right]^2 \quad (3)$$

and

$$^{14}\delta_N = ^{14}a_N - 1. \quad (4)$$

The  $^{14}\text{C}$  activity ratio  $^{14}a$  originates from Eq. (1), where  $A$  is the commonly used symbol for radioactivity expressed in Becquerel (Bq) (e.g., Friedlander et al., 1981). Recently, the symbol  $F^{14}\text{C}$  is advocated (Reimer et al., 2004a) which is equivalent to  $^{14}a_N$ . This new symbol is more “popular” and more intuitive, and therefore also followed here:

$$F^{14}\text{C} = ^{14}a_N. \quad (5)$$

Again, this symbolizes the activity ratio with respect to the standard, and includes correction for isotopic fractionation. It obviously also includes correction for background activity.

There are detailed issues involved with the relatively simple expression (3)—like the fact that the original Ox1 standard is normalized to its own  $^{13}\delta$  value of  $-19\%$  (Stuiver and Polach, 1977), or the fact that the value of the exponent in Eq. (3) is only approximately 2 (Mook and van der Plicht, 1999; Donahue et al., 1990). These details are usually not relevant for users of radiocarbon and are not further discussed here.

Radiocarbon or  $^{14}\text{C}$  ages  $T$  are based on this measured and normalized  $^{14}a_N$  value:

$$T = -8033 \ln(^{14}a_N) = -8033 \ln(F^{14}\text{C}) \quad (6)$$

which simply follows from the exponential radioactive decay law, using a half-life value  $T_{1/2} = 5568$  years:

$$\frac{T_{1/2}}{\ln(2)} = 8033. \quad (7)$$

The original half-life value as introduced by Libby (1952) is used by convention. A more accurate half-life has been measured as  $5730 \pm 40$  years (Godwin, 1962).

Note that very recently the latter value has come under discussion (Broecker, 2005). But this does not influence the radiocarbon dates in BP since these are conventional.

The  $^{14}\text{C}$  ages thus calculated are reported in BP or “Before Present” and are termed “Conventional Radiocarbon Ages”. Summarizing, this encompasses (1) measured relative to the Ox1 standard radioactivity, (2) corrected for isotopic fractionation to  $^{13}\delta = -25\%$  (3)

calculated using the conventional half-life value of  $T_{1/2} = 5568$  years and (4) the assumption of constancy of  $^{14}\text{C}$  atmospheric level during the past.

The use of the word “Present” in the unit “BP” can cause confusion because “Present” in this term corresponds to the standard activity and 1950 AD not the present day.

It is important to realize that the timescale for conventional  $^{14}\text{C}$  ages is *defined* and is referred to as  $^{14}\text{C}$  years (expressed in BP). This time scale needs to be calibrated in order to obtain calendar ages. This calibration procedure takes into account both the natural  $^{14}\text{C}$  variations and the incorrect half-life. Calibration curves are obtained by measuring the  $^{14}\text{C}$  content of samples, dated absolutely by an independent method—preferably absolute, such as dendrochronology. For calibration curves we refer to the most recent calibration issue of the journal *Radiocarbon* (vol. 46 no. 3). The present Northern Hemisphere calibration curve is Intcal04 (Reimer et al., 2004b). For marine data, calibration curves need to incorporate the  $^{14}\text{C}$  reservoir effect; a marine calibration curve has been developed (Marine04; Hughen et al., 2004). Both curves cover the time range back to 26,000 years. Beyond 26,000, no calibration curve has been recommended thus far (Notcal04; van der Plicht et al., 2004). Southern Hemisphere dates younger than 11,000 cal BP are calibrated using SHCal04 (McCormac et al., 2004). It has been recommended that Southern Hemisphere samples older than this should not be calibrated because of the uncertainties associated with the interhemispheric offset before the Holocene (McCormac et al., 2004).

Calibrated  $^{14}\text{C}$  dates are reported in calAD or calBC (Mook, 1986). In addition, calBP is used which means “calibrated or calendar years before 1950 AD”. Unfortunately, calBP is also widely used for chronologies of records based on ice cores, marine cores; ESR, U-series and luminescence dates, etc. Here “Present” not necessarily corresponds to 1950. Thus, these calBP’s are different from the  $^{14}\text{C}$  one, which is the only one clearly defined (i.e. with respect to 1950 AD). For this reason, the NGRIP team recently proposed the use of “b2k” (before 2000) as an alternative (Rasmussen et al., 2006). This becomes necessary because the difference between “Present” and “Present = 1950” obviously increases and is now well within the temporal resolution of the dating methods.

A special convention is needed for  $^{14}\text{C}$  ages close to the dating limit of 50,000 years. For  $^{14}\text{C}$  ages which are not so old, the measured activity plus error  $F^{14}\text{C} \pm \sigma(F^{14}\text{C})$  easily translates into an age  $T \pm \sigma(T)$ , using Eq. (6). For old samples, however, the errors in  $T$  become asymmetric. In addition, activities measured as e.g.  $0.01 \pm 0.10\%$  include negative values that are obviously without physical meaning. This corresponds to ages that are infinite for  $^{14}\text{C}$ . For this reason, the following convention has been agreed, based on the sigma value  $\sigma(F^{14}\text{C})$  of the measured  $^{14}\text{C}$

activity  $F^{14}\text{C}$  (Olsson 1989):

When...	then take...	to calculate age $T$
$F^{14}\text{C} < 0$	$F^{14}\text{C} = 2\sigma(F^{14}\text{C})$	$T > -8033 \ln F^{14}\text{C}$
$F^{14}\text{C} < \sigma(F^{14}\text{C})$	$F^{14}\text{C} = F^{14}\text{C} + 2\sigma(F^{14}\text{C})$	$T > -8033 \ln F^{14}\text{C}$
$F^{14}\text{C} < 2\sigma(F^{14}\text{C})$	$F^{14}\text{C} = F^{14}\text{C} + 2\sigma(F^{14}\text{C})$	$T > -8033 \ln F^{14}\text{C}$
$F^{14}\text{C} > 2\sigma(F^{14}\text{C})$		$T = -8033 \ln F^{14}\text{C}$
	$\sigma^+(T) = -8033 \ln(F^{14}\text{C} - \sigma(F^{14}\text{C}))$	
	$\sigma^-(T) = -8033 \ln(F^{14}\text{C} + \sigma(F^{14}\text{C}))$	
$F^{14}\text{C} \gg 2\sigma(F^{14}\text{C})$		$T = -8033 \ln F^{14}\text{C}$
	$\sigma^+(T) = \sigma^-(T) = \sigma(T)$	

Note that also when  $\sigma(F^{14}\text{C}) < F^{14}\text{C} < 2\sigma(F^{14}\text{C})$ , an age limit should be given despite the fact that  $\sigma^+(T)$  and  $\sigma^-(T)$  can be calculated. The reason is that for these cases  $2\sigma(T)$  is infinite because  $F^{14}\text{C} - 2\sigma(F^{14}\text{C})$  is negative.

These expressions are stated at the  $1\sigma$  (68% probability) level. When the  $2\sigma$  (95% probability) level is needed, the errors for the age can be easily calculated by replacing the  $1\sigma$  by  $2\sigma$  in the given expressions for  $T$ .

In principle, all errors in  $^{14}\text{C}$  ages  $T$  are asymmetric. However, in practice this can be ignored for the majority of  $^{14}\text{C}$  dates. For relatively young dates, the effect is insignificant; for older dates (a few half-lives) the effect is not relevant when dates and errors are rounded to their significant digits; only for old dates close to the detection limit, the effect becomes significant.

A practical example of an analysis using  $^{14}\text{C}$  measurements close to the dating limit can be found in Mol et al. (2006).

Sometimes we need to know the original  $^{14}\text{C}$  content of the sample in the year of the sample origin (such as the year a tree ring was formed). As the measured  $^{14}\text{C}$  content is valid for the year 1950, it has to be corrected for radioactive decay from the year of origin ( $t_i$ ) to 1950 using the physical (not: conventional) half-life. This yields

$${}^{14}\delta_N^i = {}^{14}a_N^i - 1, \quad (8)$$

where

$$\begin{aligned} {}^{14}a_N^i &= {}^{14}a_N \exp\{-(t_i - 1950)/8267\} \\ &= F^{14}\text{C} \exp\{\text{cal BP}/8267\}, \end{aligned} \quad (9)$$

where  $T_{1/2}/\ln(2) = 8267$  for  $T_{1/2} = 5730$  yr. This corresponds to  $\Delta$  or  $\Delta^{14}\text{C}$ , which is widely used in the literature. For a full discussion on the use of the symbols we refer to Mook and van der Plicht (1999).

Thus, this shows the natural  $^{14}\text{C}$  content of a sample, as compared with 1950.

Finally, we note that the definitions given here are valid for all existing  $^{14}\text{C}$ -dating techniques, once fractionation normalization is corrected for. They apply to conventional radiometry (both liquid scintillation spectrometry, LSC and proportional gas counting, PGC) and mass spectrometry (accelerator mass spectrometry, AMS).

For detailed examples and special cases, such as  $^{14}\text{C}$  in the hydrological cycle and dosimetry, we refer to Mook and van der Plicht (1999).

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## References

- Broecker, W.S., 2005. Invited talk at the 10th International Conference on Accelerator Mass Spectrometry, Berkeley, USA, 5–10 September.
- Donahue, D.J., Linick, T.W., Jull, A.J.T., 1990. Isotope ratio and background corrections for accelerator mass spectrometry radiocarbon measurements. *Radiocarbon* 32, 135–142.
- Friedlander, G., Kennedy, J.W., Macias, E.S., Miller, J.M., 1981. *Nuclear and Radiochemistry*. Wiley, New York.
- Godwin, H., 1962. Half life of radiocarbon. *Nature* 195, 984.
- Gonfiantini, R., 1984. Stable isotope reference samples for geochemical and hydrological investigations. Report of Advisory Group, Vienna.
- Hughen, K.A., Baillie, M.G.L., Bard, E., Beck, J.W., Bertrand, C.J.H., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Kromer, B., McCormac, F.G., Manning, S., Bronk Ramsey, C., Reimer, P.J., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Talamo, S., Taylor, F.W., van der Plicht, J., Weyhenmeyer, C.E., 2004. MARINE04 marine radiocarbon age calibration, 0–26 cal kyr BP. *Radiocarbon* 46, 1059–1086.
- Karlén, I., Olsson, I.U., Källberg, P., Killiççi, S., 1966. Absolute determination of the activity of two  $^{14}\text{C}$  dating standards. *Arkiv for Geofysik* 6, 465–471.
- Libby, W.F., 1952. *Radiocarbon Dating*. University of Chicago Press, Chicago, 124p. (Also published in Phoenix Science Series, second ed., 1965).
- Mann, W.B., 1983. An international reference material for radiocarbon dating. *Radiocarbon* 25, 519–527.
- McCormac, F.G., Hogg, A.G., Blackwell, P.G., Buck, C.E., Higham, T.F.G., Reimer, P.J., 2004. SHCal04 Southern Hemisphere calibration 0–1000 cal BP. *Radiocarbon* 46, 1087–1092.
- Mol, D., Tikhonov, A., van der Plicht, J., Kahlke, R.D., DeBruyne, R., van Geel, B., Pals, J.P., de Marliave, C., Reumer, J.F.W., 2006. Results of the Cerpoxel/Mammuthus expeditions on the Taimir peninsula, arctic Siberia, Russian federation. Third International Mammoth Conference, Yukon, Canada, May 2003. *Quaternary International* 142–143, 186–202.
- Mook, W.G., 1986. Business meeting (Trondheim). *Radiocarbon* 28, 799.
- Mook, W.G., van der Plicht, J., 1999. Reporting  $^{14}\text{C}$  activities and concentrations. *Radiocarbon* 41, 227–239.
- Olsson, I.U., 1989. The  $^{14}\text{C}$  method—its possibilities and some pitfalls, vol. 24. PACT Publications, pp. 161–177.
- van der Plicht, J., Beck, J.W., Bard, E., Baillie, M.G.L., Blackwell, P.G., Buck, C.E., Friedrich, M., Guilderson, T.P., Hughen, K.A., Kromer,

- B., McCormac, F.G., Bronk Ramsey, C., Reimer, P.J., Reimer, R.W., Remmele, S., Richards, D.A., Southon, J.R., Stuiver, M., Weyhenmeyer, C.E., 2004. NOTCAL04: comparison/calibration  $^{14}\text{C}$  records 26–50 cal kyr BP. *Radiocarbon* 46, 1225–1238.
- Rasmussen, S.O., Andersen, K.K., Svenson, A.M., Steffensen, J.P., Vinther, B.M., Johnsen, S.J., Clausen, H.B., Larsen, L.B., Bigler, M., Röthlisberger, R., Andersen, M.-L.S., Fisher, H., Ruth, U., Goto-Azuma, K., Hansson, M., 2006. A new Greenland ice core chronology for the last glacial termination. *Journal of Geophysical Research* 111, D06102.
- Reimer, P.J., Brown, T.A., Reimer, R.W., 2004a. Discussion: reporting and calibration of post-bomb  $^{14}\text{C}$  data. *Radiocarbon* 46, 1299–1304.
- Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C.H.J., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Hogg, A.G., Hughen, K.A., Kromer, B., McCormac, F.G., Manning, S., Bronk Ramsey, C., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Talamo, S., Taylor, F.W., van der Plicht, J., Weyhenmeyer, C.E., 2004b. INTCAL04 terrestrial radiocarbon age calibration, 0–26 cal kyr BP. *Radiocarbon* 46, 1029–1058.
- Stuiver, M., Polach, H., 1977. Reporting of  $^{14}\text{C}$  data. *Radiocarbon* 19, 355–363.