Radiocarbon, Vol 56, Nr 2, 2014, p 555–559 DOI: 10.2458/56.17455


# CONVENTIONS FOR REPORTING RADIOCARBON DETERMINATIONS

Andrew R Millard

Department of Archaeology, Durham University, South Road, Durham DH1 3LE, UK. Email: a.r.millard@durham.ac.uk.

**ABSTRACT.** Current conventions for reporting radiocarbon determinations do not cover the reporting of calibrated dates. This article proposes revised conventions that have been endorsed by many $^{14}C$ scientists. For every determination included in a scientific paper, the following should apply: (1) the laboratory measurement should be reported as a conventional radiocarbon age in $^{14}C$ yr BP or a fractionation-corrected fraction modern ($F^{14}C$) value; (2) the laboratory code for the determination should be included; and (3) the sample material dated, the pretreatment method applied, and quality control measurements should be reported. In addition, for every calibrated determination or modeled date, the following should be reported: (4) the calibration curve and any reservoir offset used; (5) the software used for calibration, including version number, the options and/or models used, and wherever possible a citation of a published description of the software; and (6) the calibrated date given as a range (or ranges) with an associated probability on a clearly identifiable calendar timescale.

## CONVENTIONS

Conventions for calculating and reporting radiocarbon determinations were published over 35 years ago following discussions at the 9th Radiocarbon Conference in California (Stuiver and Polach 1977). These conventions have been reaffirmed with small amendments on several occasions since then (e.g. at the 10th and 11th Radiocarbon conferences: Stuiver 1980, 1983) and some suggestions have been made for revising them but have not been formally adopted by the $^{14}C$ community (e.g. Mook and van der Plicht 1999; Nadeau and Grootes 2013). As the conventions were devised before calibration of $^{14}C$ determinations became routine, neither the original nor the revised versions make any provision for the reporting of calibrated dates. At the 21st Radiocarbon Conference in Paris in July 2012, during the debate leading to the ratification vote on the updated $^{14}C$ calibration curve, there was discussion of the conventions currently in place and the fact that they do not cover calibration of $^{14}C$ determinations. Those discussions prompted the author to propose the conventions in this article.

The idea of dating once-living materials using the radioactive decay of $^{14}C$ was conceived by Willard Libby and coworkers, and the first dates were published in 1949 (Libby et al. 1949). Over the early years of $^{14}C$ dating, the conventions developed for reporting a $^{14}C$ age assuming the Libby half-life of 5568 yr with 95% of the $^{14}C/^{12}C$ of NBS oxalic acid as the $^{14}C/^{12}C$ reference point (Flint and Deevey 1961) from which dates are calculated in years before present (BP) with 1950 as the zero point of the timescale (Flint and Deevey 1962). The conventions continued to develop (Olsson 1970) and the process culminated in international agreement of the detailed definition of a conventional $^{14}C$ age and the recommendation for the reporting of $^{14}C$ determinations as fraction modern in situations where the BP convention was not appropriate (Stuiver and Polach 1977). With minor amendments (Stuiver 1980, 1983; Long 1995; Reimer et al. 2004), these conventions are still in use today.

By the late 1950s, it was recognized that $^{14}C$ yr BP were not equivalent to calendar years before 1950, due to secular variations in $^{14}C$ production in the upper atmosphere and variations in exchange rates with other carbon reservoirs. Data sets to allow calibration of $^{14}C$ determinations to calendar years started to become available in the 1960s, and a variety of approaches and curves were proposed (summarized in Klein et al. 1980), culminating in a consensus curve based on the best available data (Klein et al. 1982). The first international endorsement of a calibration curve was at the

Proceedings of the Radiocarbon and Archaeology 7th International Symposium
Ghent, Belgium, April 2013 | Edited by Mark Van Strydonck, Philippe Crombé, and Guy De Mulder

Trondheim Radiocarbon Conference in 1985 (Mook 1986) and this has been updated periodically ever since (e.g. Stuiver et al. 1998; Reimer et al. 2004, 2009, 2013). The calibration curve endorsed at Radiocarbon conferences has never been the only one available, and various workers have used alternative data sets because they found them more appropriate for their application, or they represent some improvement on the agreed curve. Alternative methods of constructing the calendar and $^{14}$C components of a calibration curve have also been proposed, e.g. CalPal-2007$_{Hulu}$ (Weninger and Jöris 2008) or the Fairbanks calibration curve (Fairbanks et al. 2005). Consequently, although the majority of calibrated $^{14}$C determinations appearing in the literature today are based on one of the internationally agreed calibration curves, a significant minority of calibrations use other data sets. In addition, there are multiple software packages for calibration, with a number of them allowing mathematical modeling of dates, including Bacon (Blaauw and Christen 2011), BCal (Buck et al. 1999), BChron (Haslett and Parnell 2008), BPeat (Blaauw and Christen 2005), CALIB (Stuiver and Reimer 1993), CalPal (Weninger and Jöris 2008), Clam (Blaauw 2010), Fairbanks' program (Fairbanks et al. 2005), OxCal (Bronk Ramsey 2009), and others. Although simple calibrated ages differ little between packages, choice of software can have can have a significant impact on the results calibrating $^{14}$C determinations within a mathematical model. Recently, data sets and software for post-bomb calibration have also become available (Reimer et al. 2004).

Although calibration is now routine for $^{14}$C determinations, the current conventions for reporting them do not extend to the reporting of calibrated dates. Almost 3 decades ago, Mook and Waterbolk (1985:58) urged that users should "indicate the calibration curve or table used," but many authors have not followed this advice. Within the literature there is much variation in the level of detail given. Some papers do not give the uncalibrated determinations, and others report calibrated dates without indicating which software, calibration curve, and/or mathematical models were used. Many thousands of calibrated $^{14}$C determinations are now published every year. When these are published in a format that prevents the calibration calculation being verified or updated, and does not allow the data to be reused, then a significant investment is wasted and the conclusions cannot be subject to the usual scientific test of repeatability.

The following conventions (given in italics) for reporting of $^{14}$C determinations are therefore proposed. For every determination included in a scientific paper, the following should apply (recognizing that it may be appropriate to place this information in supplementary material):

1. *The laboratory measurement should be reported as a conventional $^{14}$C age in $^{14}$C yr BP or a fractionation-corrected fraction modern (the F$^{14}$C value of Reimer et al. 2004) according to the amended conventions of Stuiver and Polach (Stuiver and Polach 1977; Stuiver 1980, 1983; Reimer et al. 2004).* This ensures that the data is reusable by other scientists in the future as calibration curves change and understanding of the carbon cycle improves. To avoid confusion and errors, no attempt should be made to convert an uncalibrated determination to another timescale by simple subtraction or addition of a fixed offset (e.g. subtracting from 1950 to get a date in AD/BC).

2. *The laboratory code for the determination should be included.* This provides traceability to published preparation methods for many laboratories, and in some cases the ability to revisit samples or records even decades after the initial measurements.

3. *The sample material dated, the pretreatment method applied, and quality control measurements should be reported.* Wherever possible, biological materials should be identified to genus and preferably species. For standard pretreatments, the reporting may be by reference to a published description, though any deviation from the published protocol should be noted. Quality control

measurements are likely to include $\delta^{13}C$ values, together with measurements such as %C for charcoal or C/N ratio for proteinaceous samples. It should be indicated whether $\delta^{13}C$ values were by isotope-ratio mass spectrometry (IRMS) or accelerator mass spectrometry (AMS), as the latter should not be used for making dietary reconstructions or reservoir corrections.

In addition, for every calibrated determination or modeled date the following should be reported:

4. *The calibration curve and any reservoir offset used.* The international $^{14}C$ community periodically endorses a calibration curve for general use, but this has changed significantly with each update, so it is important to specify which version has been used. There are also situations where some other calibration curve is more appropriate. Thus, to allow replication of results the calibration curve must be specified unambiguously. In addition, when a reservoir offset is used to modify a calibration curve, the size and uncertainty of that offset are key parameters that must be reported to allow replication.

5. *The software used for calibration, including version number, the options and/or models used, and wherever possible a citation of a published description of the software.* This is essential to allow replication of calibration procedures, especially those that use mathematical models to modify the probability distribution from calibration of a single $^{14}C$ determination. Where errors in a particular version of software are identified, it also allows rapid identification of the published calibrated dates affected by the error. A probability method of calibration should be used as the intercept method of calibration results in loss of information. Any chronological models used need to be explicitly defined.

6. *The calibrated date given as a range (or ranges) with an associated probability on a clearly identifiable calendar timescale.* The "number of significant figures given in the published results should be related to the accuracy of these results" (Royal Society 1974:8). The calibrated ranges for single $^{14}C$ determinations rarely need reporting more precisely than at decadal resolution, but greater precision may be appropriate for shorter ranges resulting from the use of multiple dates in a mathematical model. Care should be taken to round only at the end of a calculation, as intermediate rounding may introduce errors. Point estimates of dates (e.g. median calibrated age) cannot represent the uncertainties involved. If point estimates are reported, this should be in addition to probability ranges. Where calibration produces more than one age range, all the ranges or a summary of their overall span should be reported. A probability such as 68% or 95% should be given for each range, and the terms "1-sigma" and "2-sigma" should not be used to describe calibrated dates as they are not meaningful in this context. The calendar timescale should be specified, for example, AD/BC, CE/BCE, cal BP, or b2k (the latter defined in Svensson et al. 2006), and the abbreviation BP should be reserved for uncalibrated $^{14}C$ determinations, which should only be reported in BP.

These conventions have been endorsed by the 41 scientists working with $^{14}C$ whose names are listed below, and they join the author in proposing these to the wider scientific community as encapsulating the minimum for good practice in the field. We recommend to authors, editors, and referees of papers in all the areas of research that utilize $^{14}C$ determinations that these should be followed as a necessary component of good scientific reporting.

## Endorsers

The scientists who have endorsed these recommendations are the following: Philippa Ascough (Scottish Universities Environmental Research Centre, UK), Peter Barta (Comenius University, Slovakia), Paolo Bartolomei (ENEA Radiocarbon Lab., Italy), Nancy Beavan (University of Otago, New Zealand), Peter Becker-Heidmann (Universität Hamburg, Germany), Maarten Blaauw (Queen's University Belfast, UK), Elisabetta Boaretto (Weizmann Institute, Israel), Mathieu Boudin (KIK-IRPA, Belgium), Chris Brodie (University of Hong Kong), Christopher Bronk Ramsey (Oxford University, UK), Caitlin Buck (Sheffield University, UK), Michael Dee (Oxford University, UK), Anna Depalmas (Sassari University, Italy), Richard Gillespie (University of Wollongong, Australia), Ricardo Fernandes (Leibniz-Labor, Kiel, Germany), Seren Griffiths (Cardiff University, UK), Pieter Grootes (Leibniz-Labor, Kiel, Germany), Tom Higham (University of Oxford, UK), Greg Hodgins (University of Arizona, USA), Matthias Hüls (Leibniz-Labor, Kiel, Germany), Olaf Jöris (MONREPOS Archäologisches Forschungszentrum und Museum, Germany), Marek Krapiec (Laboratory of Absolute Dating, Poland), Kita Macario (Universidade Federal Fluminense, Brazil), John Meadows (Leibniz-Labor, Kiel, Germany), Mihály Molnár (MTA Atomki, Hungary), M-J Nadeau (Leibniz-Labor, Kiel, Germany), Markku Oinonen (University of Helsinki, Finland), Jesper Olsen (Aarhus University, Denmark), B Schulz Paulsson (University of Kiel, Germany), Christine Prior (Rafter Radiocarbon Laboratory, New Zealand), Paula Reimer (Queen's University Belfast, UK), Nagui Sabri (Institut français d'archéologie orientale, Egypt), Richard Staff (Oxford University, UK), Thomas W Stafford (Aarhus University, Denmark), Michael Toffolo (Tel Aviv University & Weizmann Institute, Israel), Jocelyn Turnbull (Rafter Radiocarbon Laboratory, New Zealand), Lukas Wacker (ETH Zürich, Switzerland), Bernhard Weninger (Universität zu Köln, Germany), Rachel Wood (Australian National University), Antoine Zazzo (CNRS - MNHN, Paris, France), and Albert Zondervan (Rafter Radiocarbon Laboratory, New Zealand).

## ACKNOWLEDGMENTS

The creation of this paper was stimulated by a discussion with John Southon at the Paris Radiocarbon Conference. Comments from Ron Reimer, Seren Griffiths, Fiona Petchey, Maarten Blaauw, Caitlin Buck, Philippa Ascough, and many of the endorsers have led to important improvements.

## REFERENCES

Blaauw M. 2010. Methods and code for 'classical' age-modelling of radiocarbon sequences. *Quaternary Geochronology* 5(5):512–8.

Blaauw M, Christen JA. 2005. Radiocarbon peat chronologies and environmental change. *Journal of the Royal Statistical Society Series C-Applied Statistics* 54(4):805–16.

Blaauw M, Christen JA. 2011. Flexible paleoclimate age-depth models using an autoregressive gamma process. *Bayesian Analysis* 6(3):457–74.

Bronk Ramsey C. 2009. Bayesian analysis of radiocarbon dates. *Radiocarbon* 51(4):337–60.

Buck CE, Christen JA, James GN. 1999. BCal: an on-line Bayesian radiocarbon calibration tool. *Internet Archaeology* 7: http://intarch.ac.uk/journal/issue7/buck.

Fairbanks RG, Mortlock RA, Chiu TC, Cao L, Kaplan A, Guilderson TP, Fairbanks TW, Bloom AL, Grootes PM, Nadeau MJ. 2005. Radiocarbon calibration curve spanning 0 to 50,000 years BP based on paired $^{230}Th/^{234}U/^{238}U$ and $^{14}C$ dates on pristine corals. *Quaternary Science Reviews* 24(16–17):1781–96.

Flint R, Deevey ES. 1961. Editorial statement. *Radiocarbon* 3:i–ii.

Flint R, Deevey ES. 1962. Editorial statement. *Radiocarbon* 4:i–ii.

Haslett J, Parnell A. 2008. A simple monotone process with application to radiocarbon-dated depth chronologies. *Journal of the Royal Statistical Society Series C-Applied Statistics* 57(4):399–418.

Klein J, Lerman JC, Damon PE, Timothy L. 1980. Radiocarbon concentration in the atmosphere; 8000-year record of variations in tree rings; first results of a USA workshop. *Radiocarbon* 22(3):950–61.

Klein J, Lerman JC, Damon PE, Ralph EK. 1982. Calibration of radiocarbon dates: tables based on the consensus data of the Workshop on Calibrating the Radiocarbon Time Scale. *Radiocarbon* 24(2):103–50.

Libby WF, Anderson EC, Arnold JR. 1949. Age determination by radiocarbon content: world wide assay of natural radiocarbon. *Science* 109(2827):227–8.

Long A. 1995. From the editor. *Radiocarbon* 37(1):iii–iv.

Mook W. 1986. Business meeting: recommendations/resolutions adopted by the Twelfth International Radiocarbon Conference. *Radiocarbon* 28(2A):799.

Mook W, van der Plicht J. 1999. Reporting $^{14}C$ activities and concentrations. *Radiocarbon* 41(3):227–39.

Mook WG, Waterbolk HT. 1985. *Radiocarbon Dating*. Strasbourg: European Science Foundation.

Nadeau M-J, Grootes PM. 2013. Calculation of the compounded uncertainty of $^{14}C$ AMS measurements. *Nuclear Instruments and Methods in Physics Research B* 294:420–5.

Olsson IU. 1970. The use of oxalic acid as a standard. In: Olsson IU, editor. *Radiocarbon Variations and Absolute Chronology*. New York: John Wiley & Sons. p 17.

Reimer PJ, Brown TA, Reimer RW. 2004. Discussion: reporting and calibration of post-bomb $^{14}C$ data. *Radiocarbon* 46(3):1299–304.

Reimer PJ, Baillie MGL, Bard E, Bayliss A, Beck JW, Blackwell PG, Bronk Ramsey C, Buck CE, Burr GS, Edwards RL, Friedrich M, Grootes PM, Guilderson TP, Hajdas I, Heaton TJ, Hogg AG, Hughen KA, Kaiser KF, Kromer B, McCormac FG, Manning SW, Reimer RW, Richards DA, Southon JR, Talamo S, Turney CSM, van der Plicht J, Weyhenmeyer CE. 2009. IntCal09 and Marine09 radiocarbon age calibration curves, 0–50,000 years cal BP. *Radiocarbon* 51(4):1111–50.

Reimer PJ, Bard E, Bayliss A, Beck JW, Blackwell PG, Bronk Ramsey C, Buck CE, Cheng H, Edwards RL, Friedrich M, Grootes PM, Guilderson TP, Haflidason H, Hajdas I, Hatté C, Heaton TJ, Hoffmann DL, Hogg AG, Hughen KA, Kaiser KF, Kromer B, Manning SW, Niu M, Reimer RW, Richards DA, Scott EM, Southon JR, Staff RA, Turney CSM, van der Plicht J. 2013. IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. *Radiocarbon* 55(4):1869–87.

Royal Society. 1974. *General Notes on the Preparation of Scientific Papers*. London: Royal Society.

Stuiver M. 1980. Workshop on $^{14}C$ data reporting. *Radiocarbon* 22(3):964–6.

Stuiver M. 1983. Business meeting: international agreements and the use of the new oxalic acid standard. *Radiocarbon* 25(2):793–5.

Stuiver M, Polach HA. 1977. Discussion: reporting of $^{14}C$ data. *Radiocarbon* 19(3):355–63.

Stuiver M, Reimer PJ. 1993. Extended $^{14}C$ data base and revised CALIB 3.0 $^{14}C$ age calibration program. *Radiocarbon* 35(1):215–30.

Stuiver M, Reimer PJ, Bard E, Beck JW, Burr GS, Hughen KA, Kromer B, McCormac G, van der Plicht J, Spurk M. 1998. INTCAL98 radiocarbon age calibration, 24,000–0 BP. *Radiocarbon* 40(3):1041–83.

Svensson A, Andersen KK, Bigler M, Clausen HB, Dahl-Jensen D, Davies SM, Johnsen SJ, Muscheler R, Rasmussen SO, Rothlisberger R, Steffensen JP, Vinther BM. 2006. The Greenland Ice Core Chronology 2005, 15–42 ka. Part 2: comparison to other records. *Quaternary Science Reviews* 25(23–24):3258–67.

Weninger B, Jöris O. 2008. A $^{14}C$ age calibration curve for the last 60 ka: the Greenland-Hulu U/Th timescale and its impact on understanding the Middle to Upper Paleolithic transition in Western Eurasia. *Journal of Human Evolution* 55(5):772–81.