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# The use of AMS radiocarbon dating for Xia–Shang–Zhou chronology ☆

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**Abstract**

The possibility and problems of using radiocarbon dating to historical chronology are discussed. The current situation of ancient Chinese chronology and the project of Xia–Shang–Zhou chronology are introduced. A chronological study requires the AMS radiocarbon dating with high precision, high reliability and high efficiency. The Peking University AMS facility (PKUAMS) has been upgraded and a series of quality control steps were adopted. To reduce the error of calendar age, wiggle matching with serial samples should be used. Some preliminary results of Xia–Shang–Zhou chronology are presented. © 2000 Elsevier Science B.V. All rights reserved.

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## 1. Introduction

The historical chronology is always an attractive topic to persons who are interested in the origin and development of a civilization. Unfortunately, in ancient times usually the people just numbered the years within the ruling period of a King, so no absolute chronology is available. In the past decades the chronology of Egypt and Mesopotamia has been studied extensively, but radiocarbon dating did not play a very important role in those studies. The obstacle is the large error of calendar age, which is due to the natural variation of $^{14}C$ as seen in the calibration of radiocarbon age with the tree ring curve.

Chinese ancient civilization is one of the civilizations with an independent origin in human history. Different from Egypt, Mesopotamia and India, the Chinese civilization has been lasting for several thousand years and has never been interrupted. But the ancient Chinese chronology has not been well established so far. The set up of the project of Xia–Shang–Zhou chronology was driven by the following factors:

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1. the long-term desire of Chinese people and scholars;
2. the progress of chronological research in Egypt and Mesopotamia;
3. the recent archaeological discoveries about Xia–Shang–Zhou period in China;
4. the development of the wiggle matching with the Bayesian method.

Radiocarbon dating combined with wiggle matching will play an important role in that project and AMS will show its advantage of small samples and high throughput [1].

## 2. Chronology and radiocarbon dating

Radiocarbon dating has been widely used in archaeology. The typical applications are to determine the ages of relics, sites and cultural phases. But the situation of chronology, especially historical chronology, is somewhat different. Usually the historical chronology studies the ages of dynasties, kings and major events. The final goal of chronology is to obtain a chronicle as accurate as possible, in a perfect case, one year by one year without error.

In principle, radiocarbon dating is not an ideal tool for chronology. It is quite difficult to find the suitable sample for dating, which is directly related to the chronological event. The ages of sites and cultural phases may have an offset compared with the ages of kings and dynasties. Furthermore, radiocarbon dating always has an error and sometimes it might be too large to be accepted by chronologists. In general, the best method of chronology is to collect the necessary information from historical records. Unfortunately, it is sometimes difficult for the earliest history. The reasons are as follows:

1. Quite a lot of literature is not original and may have been transcribed many times, so their reliability might be problematical and different documents may introduce different results. Therefore arguments always exist in such a situation.
2. In contrast, the original historical records are most valuable. Presently, it is believed that writing appeared at least 4–5 ka ago in some earlier civilizations such as Egypt, Mesopotamia and China. The records that have already been discovered on stone and clay tablets in Egypt and Mesopotamia are really quite helpful to build the ancient chronology. But if the medium of written records is not easy to be preserved, we may miss the opportunity to find it many years later. The associated original records would also disappear forever.
3. Even if we could find the original records, some further research should still be carried out. Usually the ancient writings are unknown and must be deciphered. Also the ancient chronology usually does not give an absolute date. The ancient chronological method should be studied further. Some uncertainties could also be introduced during such a research.
4. Generally, after combining all the available original and transcribed records there may still exist some "missing links" of the chronology, which make it difficult to connect the earlier with later chronology.
5. For the earliest ages, when there was no writing or no original records to be discovered so far, we could still find some indirect records from literature but their reliability should be proved. Sometimes these records may include the component of myth and give a too long reign period for a king.

So the study of historical records is not always sufficient to establish an ancient chronology. As a supplementary tool astronomy could be used quite effectively. The typical examples are the phenomena of Sirius rising with sun in Egypt and the Venus Tablet of Ammisadupa in Babylon. But the astronomical phenomena always appear periodically, so that this method gives multi-solutions to chronology. It would be effective only when we could limit the possible time to a duration narrow enough by means of other methods and the ancient calendar is well known. In such a situation, it would be really helpful.

Another useful supplementary tool for ancient chronology is radiocarbon dating combined with archaeology and historical geography, although there are some difficulties with it as mentioned above. The main difficulty comes from the sample itself. A reliable connection between sample and king or event should be built at first. The sample is usually unearthed from a tomb or certain stratum of a site. The tomb or stratum and site may already be brought into an archaeological cultural phase. Then the archaeologists should give further information, for example, which king or which person with known relation to a certain king was buried in the tomb, or the archaeologists may point out that the site was a capital built by a certain king. If it is not possible to build such a connection, the sample will not be significant to chronology and the dating result only gives the age of an archaeological phase.

An obstacle to use radiocarbon dating for chronology is the large error of age, after converting the radiocarbon age to calendar age with the help of the calibration curve. In many cases the error of calendar age of a single sample is dominated by the shape of the calibration curve, and it does not help very much to reduce the uncertainty of $^{14}C$ age. So traditionally the use of radiocarbon dating in chronology was limited. During recent years a method called wiggle matching has been developed for calibration of calendar age. By means of wiggle matching with serial samples the error of the calendar age can be reduced, which brings a new possibility to the use of radiocarbon dating in chronology.

## 3. Project of Xia–Shang–Zhou chronology

The most authoritative book including the records of ancient Chinese history is the book Shi Ji written by Sima Qian, an official historian of Han Dynasty in about 100 BC. He collected abundant literature and carried out the textual research. According to the records in Shi Ji, the ancient Chinese dynasties before Han are Xia, Shang, Zhou and Qin (see Table 1). The King Ping of Zhou dynasty moved his capital to Luoyang in the east, so the preceding part of Zhou dynasty was called Western Zhou and the later part Eastern Zhou. Shi Ji gives a reliable chronicle of ancient Chinese history, which was generally recognized and started from 841 BC in the later period of Western Zhou. Shi Ji also gives the King's pedigree of all the dynasties since Xia, so we know all the King's names and their genealogy. But unfortunately there was no complete chronology before 841 BC to be presented in Shi Ji.

Table 1
Ancient Chinese dynasties

| Dynasties | Dates |
|---|---|
| Xia | ?–? BC |
| Shang | ?–? BC |
| Zhou | |
| Western Zhou | ?–771 BC |
| Eastern Zhou | 770–252 BC |
| Qin | 252–207 BC |

In fact, the argument about the age of some ancient Chinese historical events appeared even earlier, at least since 300 BC. One important example is the question about the year that King Wu of Zhou dynasty attacked and overthrew the Shang dynasty. There are over 40 versions of it spreading over more than 100 years from 1127 to 1018 BC, although this event was only about 200 years before 841 BC. There are also significant arguments on the accumulated years of Xia and Shang dynasties.

Due to lack of a direct proof, some experts even doubted whether the dynasties Xia and Shang really existed. An important direct proof of Shang dynasty was discovered in 1899, when Wang Yirong found a carving inscription on the surface of a kind of Chinese medicine. That medicine was called Longgu (dragon bone) for long time and was proved later, as oracle bone of the imperial court of Shang dynasty. Since then about 150,000 pieces of oracle bones with inscriptions were unearthed (Fig. 1). The site was also recognized as the final capital of Shang dynasty. The oracle bone inscriptions recorded the King's activities, war, sacrificial offerings and important astronomical phenomena. The King's names, their genealogy and the pedigree learned from those inscriptions could coincide well with the book Shi Ji.

The Chinese archaeology has developed rapidly since 1949, especially during the recent two decades. A lot of sites and tombs belonging to the period of Xia–Shang–Zhou dynasties were discovered. Various archaeological cultures of that period were clearly understood. Some sites of an-

Fig. 1. Oracle bone with inscription. The top-left corner has been cut off for sampling, which was renovated later.

cient cities could be recognized as the capitals of Xia, Shang and Zhou dynasties. Lots of bronze artifacts of the Shang and Zhou dynasties were unearthed, too. Some bronze artifacts of late Shang and Zhou dynasties have inscriptions, which supplied another thread to study chronology.

The project of Xia–Shang–Zhou chronology started in 1996 as a major national research project. The objective of the project is to establish a chronological frame for Xia, Shang and Zhou in some detail based on the scientific evidence. The project has two main research areas. One is to collect the astronomical phenomena from historical records and to calculate the date of those phenomena by means of modern software. Another is to unearth, sort out and study the typical sites and tombs, to collect serial samples and to determine their age by radiocarbon dating and wiggle matching. The astronomy method can only fix limited points in the chronological frame, although some point may be significantly important. So the radiocarbon dating will play an important role to establish the whole chronological frame.

Both decay counting and AMS are used for that project, but AMS has a special advantage due to its characteristics of small samples and high throughput. For example, the oracle bones and some important small samples can be measured only with AMS. To meet the requirements of Xia–Shang–Zhou chronology, the AMS facility and the sample preparation system at Peking University have been upgraded, the wiggle matching method has been investigated, and a close collaboration among physicists, chemists and archaeologists has been established.

## 4. AMS measurement

The AMS $^{14}C$ measurement for archaeological chronology should have high precision, high reliability and high efficiency. These three "Hs" are also the main objectives of the PKUAMS upgrade. Generally, the high sensitivity is an important (and essential) objective of AMS measurement too. But for Xia–Shang–Zhou chronology, it is not a limiting factor because the sample age is usually less than 4 ka BP. However, the stability of the background level really has an effect on the measuring accuracy. In typical situations, 20% variation of the background may introduce a 0.1 pMC shift for the sample. The measuring precision mainly depends on the stability of the beam line components, the "flat-top" transmission property, and the variation of ion source emittance during the measurement (for example, the "crater" effect). There are two aspects of reliability: facility running and dating results. The high reliability of the dating results demands to prevent obvious systematic errors, which is even more important than high precision. The systematic error may come from both sample preparation and $^{14}C/^{12}C$ measurement. There are also two aspects of efficiency:

utilization of sample material and utilization of time. The former is important for small samples and the latter for throughput.

The details of the upgrade of the PKUAMS facility and its $^{14}C$ sample preparation laboratory are given by other papers in this conference proceedings [2,3]. The room temperature and the humidity of the AMS hall and the mains have been stabilized to improve the running environment, too. The performance of PKUAMS has been significantly improved after the upgrade. Even so, some special quality control (QC) steps should be adopted to ensure the reliability of measuring results. Our QC steps include:

(1) *Machine error analyzing and reducing*. The machine error $\sigma_m$ can be calculated from the formula [4]

$$\sigma_m^2 = s^2 - \sigma^2, \tag{1}$$

where $s$ is the external error, estimated from the variance of repeated measurements, and $\sigma$ is the internal error, mainly from the $^{14}C$ counting statistics. The machine error is either target dependent or time dependent. If flat-top transmission is realized, most of the rest machine error might come from the ion source, especially the variation of sputtering area geometry with target and time. This may slightly change the electrical field distribution, thus changing the beam emittance. So it is important to keep the same geometry around the target holder for all the different targets and during the whole time of the measurement.

(2) *Standardized beam tuning procedure*. Usually the fractionation is beam-path dependent. When one tunes the beam from ion source to detector, many different beam-paths can be selected by the different combination of beam line component parameters, especially in the situation of flat-top transmission. A standardized beam tuning procedure ensures the reproducibility of the beam path, thus keeping the fractionation as constant as possible. To store the running parameters in a computer is helpful for the consecutive beam tuning.

(3) *Well-designed measuring procedure and data manipulation program*. AMS $^{14}C$ measurement is a relative measurement. The measuring procedure and corresponding data manipulation should satisfy the comparability of unknown sample with standard sample to an extent as great as possible, if high precision is required. In such a situation the sample arrangement on the target wheel and the measuring duration should be reasonable. The data manipulation program should not only calculate the age but also check the data distribution.

(4) *Multi-standards*. Many laboratories now use two different standards (for example, OX-I and OX-II) in AMS $^{14}C$ measurement. The ratio of the two standards gives a measure of the reliability of the dating results. PKUAMS uses OX-I as main standard material. OX-II, ANU and the Chinese sucrose charcoal (CSC) are used as the second standards. IAEA C-series samples are also measured periodically.

(5) *Multiple targets*. For high precision $^{14}C$ measurement it is better to divide a sample into 2–4 sub-samples and load them into different targets, which should be measured referring to different standards, and in the best way, arranged in separate runs, so that the degree of freedom would not be lost. Then a consistency check with respect to the mean values evaluated from the measurement of each target should be taken. The consistency check could be either a $t$-test for two targets or variance analyzing $F$ test for three or more targets. If the test result is negative, the sample should be reanalyzed.

(6) *Intercomparison*. The intercomparison can not only check the $^{14}C$ measurement but also the sample preparation, so it should be carried out regularly. PKUAMS has arranged an intercomparison with the IsoTrace laboratory, Toronto University, for the Xia–Shang–Zhou chronology. Seven samples were measured in both laboratories. Six samples gave a difference within $1\sigma$, and one within about $2\sigma$.

## 5. Wiggle matching

It is well known that the calibration of radiocarbon age to calendar age with the tree ring calibration curve will usually enlarge the age error due to the wiggles of the calibration curve. In a typical situation, the enlargement factor may be about two. So if the $^{14}C$ measurement has a precision of 0.4%, the $1\sigma$ of the radiocarbon age is 32 a and $1\sigma$ of the calendar age is about 65 a. If we take a confidence level of 95%, the total confidence interval ($\pm 2\sigma$) of the calendar age will be 260 a. In fact, the converted error is sensitive to the age value, i.e., it depends on which section of the curve will be used. Occasionally, we may have the best situation and the error of the calendar age is reduced considerably (Fig. 2). But more often, the data may fall into the "wiggle platform" section and even the $1\sigma$ error could be more than 300 a (Fig. 3). In such a situation the high precision does not reduce the uncertainty of the calendar age very much. So generally the chronologist will not be satisfied with the radiocarbon dating.

The idea of wiggle matching was suggested quite early. In principle, if we have a series of samples with certain sequence, their radiocarbon age will go up or down with the curve's wiggles. So

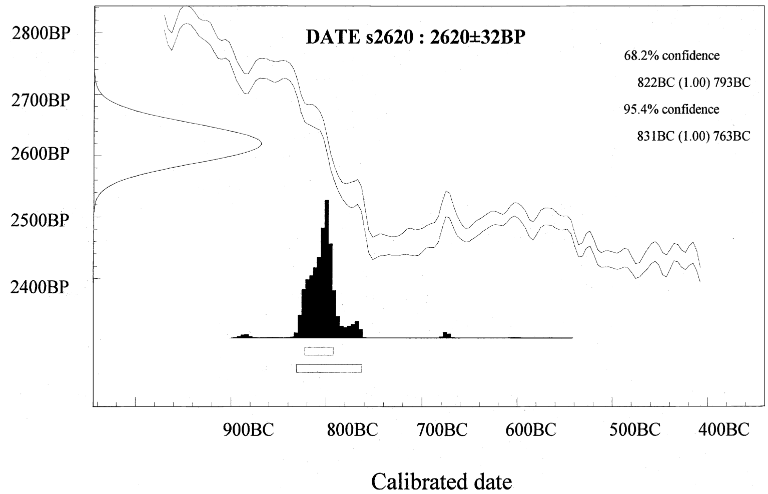


Fig. 2. Example of calendar age calibration with small age error. $1\sigma$ is 30 a, $2\sigma$ is 70 a.

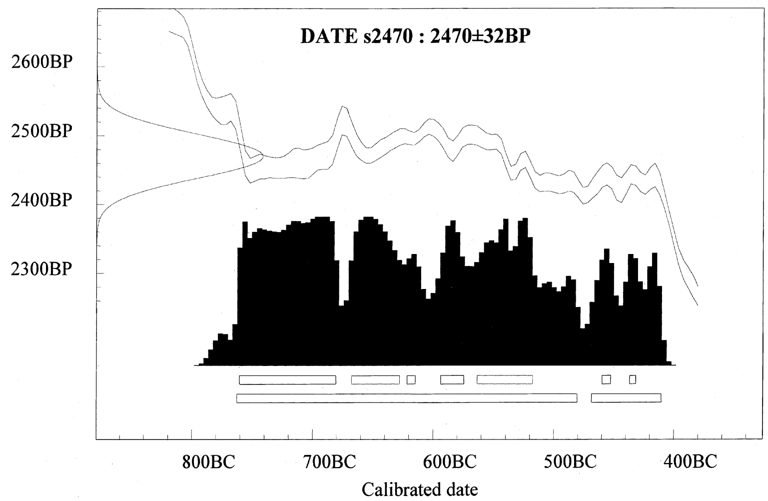


Fig. 3. Example of calendar age calibration with large age error. $1\sigma$ is 320 a, $2\sigma$ is 350 a.

we can fix their calendar age better by matching the group of radiocarbon ages with the calibration curve. There are three categories of sample series:

1. Gap-known sample series like the samples taken from a tree ring section.
2. Sequence-known sample series, typically a geological profile.
3. Phase-known sample series, for example the archaeological samples unearthed from a site.

In such a case, the samples can be grouped into different phases according to the cultural phases. The phases have a sequence but it might be difficult to put the samples of a phase into a sequence.

The early method of wiggle matching is curve fitting either manually or optimized by least squares. This method is effective to gap-known sample series (or gap-equal samples) only. In 1991 Buck et al. [5] suggested that the Bayesian method can be used for wiggle matching. In the ensuing years, this group gave quite a number of Bayesian method applications in archaeology and geology.

The Bayes' theorem is based on the formula

$$P'(t) = L(t)P(t), \tag{2}$$

where $P'(t)$ is called the posterior distribution, which is the probability distribution we want to obtain. In our case, it is the probability distribution of calendar age. $L(t)$ is a normalized likelihood distribution, calculated from the measured radiocarbon age and tree-ring calibration curve. $P(t)$ is called the prior distribution, which is the probability distribution we have already known, before the measurement. For a single sample, the prior distribution should be uniform in time in a wide interval. For a sample in a gap-known or sequence-known series, the prior distribution will be restricted by other samples in the series. As the result, the posterior distribution becomes narrower and the error of calendar age is reduced.

An available program, which can be used for wiggle matching with Bayesian method, is OxCal developed by Bronk Ramsey [6] in Oxford. OxCal can deal with all three categories of sample series and a Monte Carlo sampling method is used.

We have investigated the Bayesian method and the OxCal program, and tried to do wiggle matching with OxCal for the Xia–Shang–Zhou chronology. From our experience we suggest that some points should be given more attention.

1. *Series selection.* The time span of whole series should not be too short, but the gap of samples should not be too long. It is better to have at least two waves for the span, and shorter than half a wave for the gap.
2. *Sample number.* Every phase should have enough samples, which should spread as wide as possible. The number of samples in different phases should have a balance roughly.
3. *Terminal effect.* After wiggle matching, usually the samples in the middle phase have less error, but the samples in terminal phases have larger errors. If we want to study the dynasty replacement, it is better to construct a series to include the phases of both dynasties. Otherwise the command BOUND can be used to estimate the boundaries of a phase or a series of phases. But we can only insert this command between phases if they are abutting phases.
4. *Calibration curve shape.* The result of wiggle matching depends to a great extent on the shape of the calibration curve. Special care should be taken for the intervals with "wiggle platform", for example the interval 760–400 BC, in which case the sample series should be designed carefully.

## 6. Preliminary results and discussions

About 200 samples have been measured by PKUAMS for the project of Xia–Shang–Zhou chronology so far, including the samples for methodological research. Most of the samples can be put into 8 series for wiggle matching. These series include 7 site/tomb series, and a special series is those for the oracle bone samples. More samples will be measured in the near future. All the results will be published somewhere in succession.

From the results of AMS $^{14}C$ dating combined with decay counting $^{14}C$ dating, astronomy and other methods, a preliminary chronological frame of Xia, Shang and Zhou dynasties have been derived as shown in Table 2. Further research has to be carried out for improving the frame.

Table 2
Preliminary chronological frame of Xia, Shang and Zhou dynasties

| Dynasties | Dates |
|---|---|
| Xia | ca. 2070–1600 BC |
| Shang | ca. 1600–1046 BC |
| Western Zhou | 1046–771 BC |

The whole dating procedure includes the following steps:
1. sample collection and selection;
2. sample pretreatment and component extraction;
3. graphite preparation;
4. $^{14}C$ measurement;
5. wiggle matching.

Steps 1 and 5 are especially important to a chronological study. How we can use the dating results best, depends on the extent to which we know the sample's meaning. The final results obtained with wiggle matching also largely depend on the relation of samples in a series, i.e., the prior distribution in Bayesian statistics. Most of samples for chronological study are charcoal and bone. The charcoal sample may give an age shift from the true value of the site. The age of charcoal from a log may be too old, and the age of charcoal deposited in acid sandy soil may be too young [7]. So it is important to collect the charcoal from branches if possible and to learn the burying environment. Usually bone samples can give more reliable ages than charcoal, if the suitable component can be extracted and dated. But some study reported that the bone metabolism will become slow after the twenties, so dating a bone of a very old person may give a date several tens of years earlier than the date that the person died [8].

Step 2 is also worth to pay attention to. To select the right component is the basis of a right dating result. For bone samples, gelatin produced from collagen usually reflects the bone's age best if the collagen content is high enough.

Steps 3 and 4 are standard procedures for AMS. But for chronological studies the measuring precision should be higher, otherwise a small age shift might occur during wiggle matching.

## 7. Conclusions

AMS $^{14}C$ measurements have been used in archaeology for long time with lots of benefit, but for chronological study further research is necessary. The measurements should have high precision, high reliability and high efficiency. The quality control steps should be arranged. Wiggle matching can reduce the error of the calendar age, and is helpful to chronological studies. The sample collection and component extraction are important links for $^{14}C$ dating. The effective collaboration of physicist, chemist and archaeologist is absolutely necessary to get good results.

The project of Xia–Shang–Zhou chronology is an attempt to combine the experts from many different disciplines in China. After upgrade, PKUAMS has clearly improved its performance. With serial samples and the wiggle matching method, AMS $^{14}C$ measurement will play an important role in Xia–Shang–Zhou chronology.

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