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RESEARCH ARTICLE

Attaining Accuracy and Precision of Measuring Containers During the Qin Dynasty

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Abstract
This article explores how Qin Dynasty bureaucrats attained accuracy and precision in producing and designing measuring containers. One of the salient achievements of the Qin empire was the so-called unification of measurement systems. Yet measurement systems and the technological methods employed to achieve accuracy and precision in ancient China have scarcely been explored in English-language scholarship. I will examine the material features of the containers and reconstruct the production methods with which the clay models, molds, and cores of the containers were prepared before casting. I also investigate the inscriptions on the containers to determine whether they were cast or engraved. In so doing, I supply the field of Qin history with additional solid evidence about how accuracy and precision were defined in the Qin empire.

Keywords: Qin Dynasty; accuracy; precision; measuring containers; core

Introduction

The process by which the state of Qin came to unify China has long been the subject of much academic study.[1] One of the salient achievements of the Qin empire, often mentioned by scholars, was the unification of measurement systems, including lengths, volumes, and weights. Qin Shihuangdi 秦始皇帝 (r. 246–221–210 BCE) and Qin Ershi 秦二世 (r. 210–207 BCE) each issued an edict about the regulation of the measurement

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[1]Liu Yang, "Objects from the Qin Dynasty," in *China's Terracotta Warriors: The First Emperor's Legacy*, edited by Liu Yang et al. (Minneapolis: Minneapolis Institute of Arts, 2012), 229–95; Yuri Pines et al., eds., *Birth of An Empire: The State of Qin Revisited* (Berkeley: University of California Press, 2014); Charles Sanft, *Communication and Cooperation in Early Imperial China: Publicizing the Qin Dynasty* (Albany: State University of New York Press, 2014).

systems (in 221 BCE and 209 BCE respectively), and had the edicts cast or engraved on the empire's standard containers and weights.[2] But there has been relatively little study of the means by which Qin empire bureaucrats attained accuracy and precision in measurement standards. Past scholars have focused on the conversion of Qin volumetric units to present-day metric units and on textual and philological analysis of the two edicts. They did not pay attention to issues such as how the standard measures and weights, and especially the measuring containers, came into being. We therefore lack a solid historical understanding of how Qin bureaucrats established the measuring standards, how they designed and produced the standard measuring containers, and how they ensured the precision of capacity and volume measurement. This article proposes to study the history of the attainment of accuracy and precision during the Qin Dynasty by focusing on the production and design of the measuring containers.

Literature Review

History of Technology

Measurement systems and technological methods by which accuracy and precision were achieved in ancient China have scarcely been explored in English scholarship, despite their fundamental importance in changing the ways technology developed in China. The grand project, "Science and Civilization in China," initiated by Joseph Needham and continued by his successors, includes studies of mathematics, physics, mechanical engineering, and other subjects, all concerning accuracy and precision. But measurement systems and technological methods of producing the standard measures throughout multiple time periods in China were not undertaken as individual topics of inquiry, nor were they compared to other measurement systems or technological methods from other ancient civilizations.[3] Recently these topics have begun to attract attention from textual historians whose primary concern has been with the implementation of the measurement systems in different dynasties, with particular emphasis on the Qin Dynasty.[4] But the technological methods used to produce the standard measures have not been systematically explored in research to date.

[2]For the original version and translation, see Charles Sanft, *Communication and Cooperation*, 59–60. See also Michael Loewe, *Problems of Han Administration: Ancestral Rites, Weights and Measures, and the Means of Protest* (Leiden: Brill, 2016), 180–84.

[3]For the studies of measurement systems in ancient Mesopotamia, see Eleanor Robson, *Mathematics in Ancient Iraq: A Social History* (Princeton: Princeton University Press, 2008), 115–23; E. Ascalone and L. Peyronel, "Two Weights from Temple N at Tell Mardikh-Ebla, Syria: A Link between Metrology and Cultic Activities in the Second Millennium BC?" *Journal of Cuneiform Studies*, 53.1 (2001), 1–12; M. A. Powell, "Ancient Mesopotamian Weight Metrology: Methods, Problems and Perspectives," in *Studies in Honor of Tom B. Jones* (Alter Orient und Altes Testament 203), edited by M.A. Powell and R.H. Sack (Kevelaer/Neukirchener-Vluyn: Butzon & Bercker/Neukirchener, 1979), 71–109. For modern Europe, see Terry Quinn, *From Artefacts to Atoms: The BIPM and the Search for Ultimate Measurement Standards* (New York: Oxford University Press, 2012); Ken Alder, *The Measure of All Things: The Seven-Year Odyssey that Transformed the World* (London: Abacus, 2002). But these sources, similar to those of Chinese historians, focus on the measurement systems, but not on the actual designing and production of the measures.

[4]Qiu Guangming 丘光明, "Shilun Zhanguo hengzhi" 試論戰國衡制, in *Zhongguo gudai duliangheng lunwenji* 中國古代度量衡論文集, edited by Henan Sheng Jiliangju 河南省計量局 (Zhengzhou: Zhongzhou Guji, 1990), 382–403; Qiu Guangming et al., *Zhongguo kexue jishu shi: duliangheng juan* 中國科學技術史：度量衡卷 (Beijing: Kexue, 2001); Michael Loewe, *Problems of Han Administration*.

Conversion of Qin Units to Metric Units

Extant Qin period measuring containers are made of either bronze or pottery.[5] Currently scholars have devoted a great portion of their work to the study of the conversion of Qin volumetric units into modern-day metric units and have attempted to trace their origins back to earlier periods.[6] The Qin containers were usually measured in units such as *tong* 甬/桶 (20,000 milliliter/ml), *dou* 斗 (2,000 ml), and *sheng* 升 (200 ml). Scholars have come to a consensus that the modern equivalence of one Qin *sheng* is about 200 ml.[7]

For example, there is a famous bronze measuring container housed in the Shanghai Museum, traditionally called the "Shang Yang" *fangsheng* 商鞅方升 (the "Shang Yang" cuboidal container; Figure 1, left).[8] Its inscription includes a description of Shang Yang (ca. 390–338 BCE), when he bore the official title of "Daliangzao" 大良造 (the Greater and Superior Leader of the [Sovereign's] Accomplished).[9] Yang has several names recorded in history, such as Gongsun Yang 公孫鞅 (his original name), Wei Yang 衛鞅 (Yang from the Wei state), and Shang Yang 商鞅 (Yang, the Lord of Shang (Shang Jun 商君)). Scholars currently date this container to approximately 344 BCE.[10] Its inscription also describes the volume of the container: "shiliu cun wufencun-yi wei sheng" 十六寸五分寸壹為升, which literally means "16.2 [cubic] *cun* is [one] *sheng*." The length, width, and depth of the capacity of the cuboidal container are 12.5, 6.97, and 2.3 cm and its volume is approximately 202 cubic cm/202 ml. Scholars including Qiu Guangming 丘光明, Tang Lan 唐蘭 and Ma Chengyuan 馬承源 thus deduced that one *sheng* was about 202 ml in the 344 BCE Qin state.[11] According to this inscription, these scholars continued to convert Qin *cun* 寸 and *chi* 尺, the measuring units of length, into metric units. Since the capacity of the "Shang Yang" cuboidal container is 202 cubic cm or 16.2 cubic Qin *cun*, they deduced

[5]Qiu Guangming et al., *Zhongguo kexue jishu shi*, 180, chart no. 10-3. There were probably containers made of organic materials, such as wood, as well; but they have likely all decayed.

[6]Ma Chengyuan 馬承源, "Shang Yang *fangsheng* he Zhanguo liangzhi" 商鞅方升和戰國量制," in *Zhongguo gudai duliangheng lunwenji* 中國古代度量衡論文集, 254–60; Qiu Guangming, "Shilun Zhanguo hengzhi;" Tang Lan 唐蘭, "Shang Yang liang yu Shang Yang liangchi" 商鞅量與商鞅量尺, in *Zhongguo gudai duliangheng lunwenji*, 56–63; Qiu Guangming et al., *Zhongguo kexue jishu shi*, 166–69, 178–85; Loewe, *Problems of Han Administration*, 180.

[7]Qiu Guangming et al., *Zhongguo kexue jishu shi*, 167, chart no. 9-19, item no. 4, and 168.

[8]Accession number (no.) in the Shanghai Museum collection, 44331. See Guojia Jiliang Zongju 國家計量總局 et al., *Zhongguo gudai duliangheng tuji* 中國古代度量衡圖集 (Beijing: Wenwu, 1984), 44; Qiu Guangming et al., *Zhongguo kexue jishu shi*, 166–68. See also Chen Peifen 陳佩芬, *Xia Shang Zhou qingtongqi yanjiu* 夏商周青銅器研究, vol. 6 (Shanghai: Shanghai Guji, 2004), 470–73, no. 641. I call objects of this type "containers" in this article, as they include capacity measures and other objects that bear similar shapes but did not really serve as standard measures.

[9]For an account of the life of Shang Yang, see Yuri Pines, *The Book of Lord Shang: Apologetics of State Power in Early China* (New York: Columbia University Press, 2017), 7–24. Translation of the title *Daliangzao* 大良造 is based on the translation of *Dashangzao* 大上造 in Anthony J. Barbieri-Low and Robin D.S. Yates, *Law, State, and Society in Early Imperial China: A Study with Critical Edition and Translation of the Legal Texts from Zhangjiashan Tomb no. 247* (Leiden: Brill, 2015), vol. 1, xxii, section 1.5, "Early-Han Orders of Rank Mentioned in the Zhangjiashan Legal Texts."

[10]Qiu Guangming et al., *Zhongguo kexue jishu shi*, 166–68; Chen Peifen, *Xia Shang Zhou qingtongqi yanjiu*, vol. 6, 471.

[11]Qiu Guangming, "Shilun Zhanguo hengzhi;" Tang Lan, "Shang Yang liang yu Shang Yang liangchi;" Ma Chengyuan, "Shang Yang *fangsheng* he Zhanguo liangzhi."

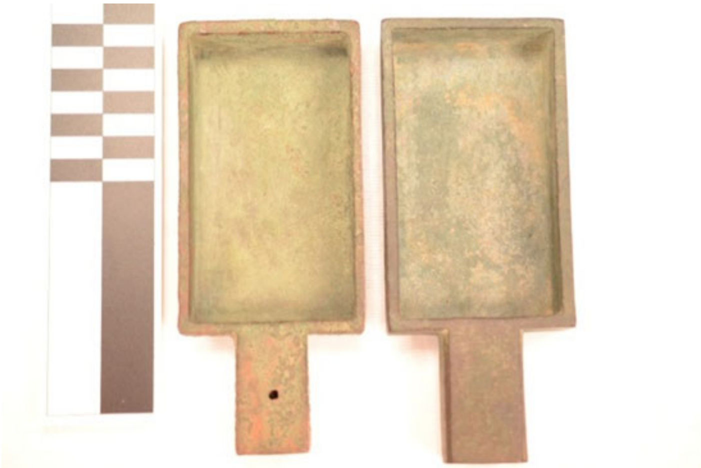

Figure 1. The "Shang Yang" cuboidal container (left, accession no. 44331, length of the entire object 18.7 cm; dimensions of the cuboidal cavity: l. 12.4774 cm, wid. 6.9742 cm, dep. 2.323 cm, v. 202.15 cm^3; w. 700 g) and the Qin Shihuang cuboidal container (right, accession no. 46425, length of the entire object 19 cm, dimensions of the cuboidal cavity: l. 12.47 cm, wid. 6.897 cm, dep. 2.51 cm, v. 215.65 cm^3). Ca. 221 BCE. Collection of the Shanghai Museum. Photo by the author.

that one cubic Qin *cun* is approximately 12.48 cubic cm. Thus one Qin *cun* is 2.32 cm and one Qin *chi* is 23.2 cm.[12]

Considering the variations of the actual volume and the corrosion built on the walls of the container, scholars have determined that one Qin *sheng* was approximately 200 ml. When a Warring States period (475–221 BCE) bronze *ding* 鼎 was excavated from Ningxia Guyuan 寧夏固原, bearing an inscription of "Xianyang yi *dou* san *sheng*" 咸陽一斗三升,[13] Qiu Guangming and his colleagues continued to reconstruct the conversion of the Qin measurement units.[14] The inscription of the Guyuan *ding* says that the capacity of the *ding* should be one *dou* and three *sheng* (2000 + 200 x 3 = 2600 ml), while the actual capacity of this *ding* is merely 2500 ml. Consequently Qiu Guangming and his colleagues attempted to reconstruct that the actual capacity of one *sheng* in the Warring States period Qin state was about 192 ml. By utilizing many more examples, they concluded that the pre-imperial Qin volume system was similar to that of the imperial Qin system, despite the existence of variations.

This type of research is adequate for us to understand the conversion from Qin units to metric units, which we may rely on in future studies. But we should further illustrate the picture of the attainment of accuracy in measure in the Qin empire.

Philological Study of the Edicts

Past scholars' primary interests of the Qin measurement policy lie at the philological study of the imperial edicts regarding the regulation of measurement

[12]202 cubic cm/16.2 cubic Qin *cun* = 12.48 cubic cm (1 cubic Qin *cun* = 12.48 cubic cm; 1 Qin *cun* = 2.32 cm; 1 Qin *chi* = 10 Qin *cun*; thus 1 Qin *chi* = 23.2 cm).

[13]This inscription translates literally as "the city of Xianyang, one *dou* and three *sheng*."

[14]Qiu Guangming et al., *Zhongguo kexue jishu shi*, 167, chart no. 9-19, item no. 4, and 168.

systems.[15] Past scholars devoted much effort to the transcription and translation of the edicts, analysis of single characters, and semantic interpretation and separation of different sentences. Different versions of the transcribed and punctuated edicts have appeared and drawn attention from these scholars. They have also been keen to associate the edicts with historical records from Sima Qian's 司馬遷 (ca. 145–86 BCE) *Shiji* 史記 to explain how the Qin unified China with the measurement policy.

Methodology

Based on previous scholars' achievement and contribution, I wish to reconstruct the history of the attainment of accuracy and precision in the volumetric system during the Qin Dynasty and in the future relate these findings to the ways in which the awareness of the Qin empire was cultivated among the populace.[16] I hope to first investigate what accuracy and precision meant to the Qin producers and users of the measuring containers. Establishing accuracy and precision was essential in all engineering and technological projects; this was extremely important in the study of all the grand infrastructure, palaces, and cemeteries building projects of the Qin empire. Did accuracy and precision entail following a single set of standards in Qin times? As Charles Sanft implies, there may have been more than one set of measurement systems extant even in the relatively unified Qin empire.[17] If the Qin bureaucrats who controlled the volumetric system were not following a single set of standards, how in turn did producers and users define accuracy and precision? And how did they handle multiple sets of standards and ultimately produce accurate measurements? I propose to begin by examining material features of the measuring containers. Close examination of the containers with the assistance of scientific analysis and 3D scanning technology will bring a new set of data to studies of this type.

The Production of Containers

I first explore how the clay models, cores, and molds of the bronze containers were prepared. This will help us relate the actual production methods to the definition and creation of accuracy and precision during the Qin Dynasty. First, we need to take account of the corrosion that has developed on metal surfaces of the containers and which has thereby increased the thickness of the walls, and thus altered the volume of the containers. By studying how the clay models, cores, and molds of the containers were prepared, we can go back to the original stage before corrosion had developed, and can thereby achieve a better understanding of how producers thought about the creation of volume.

[15]Original version and translation from Sanft, *Communication and Cooperation*, 59–60. See also Kin Sum (Sammy) Li, "To Rule by Manufacture: Measurement Regulation and Metal Weight Production in the Qin Empire," *T'oung Pao* 103.1–3 (2017), 30–32.

[16]See the study of the production and design of metal weights in Li, "To Rule by Manufacture," 1–32; and Kin Sum (Sammy) Li, "The Design Origins of Qin Metal Weights," *Artibus Asiae* 77.1 (2017), 91–110. Li, "To Rule by Manufacture," addresses the importance of studying the relationship between the governance of the empire and the production of the metal weights. I hypothesize there that weight production methods were determined by the government's political agenda, which was concerned with communicating its regulation policy to its subordinates. See also Sanft, *Communication and Cooperation*. "The Design Origins of Qin Metal Weights," discusses the origins and development of the designs of the metal weights. The Qin weight designers seem to have deliberately controlled the appearance of the weights and demonstrated no attempts to create completely innovative designs.

[17]Sanft, *Communication and Cooperation*, 72–73.

Producers of the containers had to first create clay models and molds and pour molten bronze into the molds decorated with patterns and the characters of the imperial edicts in negative.[18] When the molten bronze had solidified, they had bronze containers with the patterns and edicts in the positive. However, the question of whether the casters began decorating on the models or molds awaits further examination. If they began by decorating on the models, they would have carved the patterns and edicts in positive form on the models (the decorated models appear virtually identical to the final bronze containers), thereby producing visually straightforward examples. This method would have required them to invest the decorated models with soft clay and wait for the clay to dry. They would then have removed the clay from the models to obtain the molds for casting. If, on the other hand, they began by decorating on the molds, they would have had to carve the patterns and edicts in negative form, or mirror-reverse fashion, onto the molds, which could have created a mold for casting. Since we do not have any textual record mentioning these processes, we will have to examine remaining casting traces on the bronze containers to determine which method the Qin casters most likely adopted.

Casting Inscription and Decorated Models

I argue that many of the containers in question originated from decorated clay models. The most solid evidence comes from my observation that most of the inscriptions on the containers were cast rather than engraved,[19] since the shape of the containers is relatively simple, and producers could well have begun by decorating on the molds. A definitive answer as to whether decorated models or molds were made first has always seemed elusive at surface level. But it does seem clear that the creation of any inscription containing multiple characters depended on carving the characters onto a clay model. The clay model provided a soft and easy-to-carve platform to create each stroke of the characters. Whereas for a mold maker to carve all the characters in mirror-reverse fashion onto the mold surface will always be much more difficult.

The well-known "Shang Yang" cuboidal container provides a clear clue to answering these questions. The inscription on the "Shang Yang" cuboidal container can be divided into four parts: the Qin Shihuangdi 221 BCE edict, the record of Yang and the volume of the measure, and two place names (Table 1 and Figure 2):[20]

Table 1. Inscriptions on the "Shang Yang" cuboidal container.

Positions of the inscriptions on the "Shang Yang" cuboidal container	Bottom (central rubbing in Figure 2)	Left wall (left rubbing)	Front wall (top rubbing)	Right wall (right rubbing)
Contents of the inscriptions	Qin Shihuangdi's 221 BCE edict[21]	Dates, historical incident, name of Yang, his official title, and volume of the measure	Chongquan 重泉[22]	Lin 臨[23]

[18]See Robert Bagley, "Anyang Mold-making and the Decorated Model," *Artibus Asiae* 1 (2009), 39–90; Bagley, "Shang Ritual Bronzes: Casting Technique and Vessel Design," *Archives of Asian Art*, 43 (1990), 6–20; Rose Kerr and Nigel Wood, *Science and Civilisation in China*, vol. 5: *Chemistry and Chemical Technology*, part XII: *Ceramic Technology* (Cambridge: Cambridge University, 2004), 399–407.

[19]The inscription on the Qin bronze weights was usually cast and not engraved. See Li, "To Rule by Manufacture," 22.

[20]Chen Peifen, *Xia Shang Zhou qingtongqi yanjiu*, vol. 6, 471–73.

Translation of the inscription on the left wall:

[In the] eighteenth year, [the state of] Qi sent multiple ministers to pay [the state of Qin] an official visit.
On the day *yiyou* of the twelfth month in the winter of [the same year]. Yang, the Greater and Superior Leader of the [Sovereign's] Accomplished.
Volume [of the container] 16.2 [cubic] *cun* is [one] *sheng*

十八年，齊遣卿大夫眾來聘。
冬十二月乙酉，大良造鞅。
爰積十六寸五分寸壹為升。[24]

I observe that the 221 BCE edict and the place name "Lin" were cast, while on the other hand the record about Yang and the volume of the container and the place name "Chongquan" were engraved. Figure 3 demonstrates two characters of the 221 BCE edict, *ming* 明 and *yi* 壹 (center and right). The width of the strokes suggests that the characters could not have been engraved. It would appear that each character was instead first created on the clay model of the container by chiseling away the clay in carving out the strokes. This is why each stroke appears wide and smooth. The two characters can be compared to other cast characters on the Dagui 大騩 weight in the collection of the Nanjing 南京 Museum (Figure 3, left).[25] The width of the strokes of the characters, *wan* 綰 and *fa* 灋, also belonging to the 221 BCE edict, clearly shows that the inscription was cast and not engraved.

By way of contrast, then, what do engraved characters look like? The left image of Figure 4 displays two engraved characters on one of the Jin Hou Su 晉侯穌 bells. Ma Chengyuan and others agree that this inscription was engraved by a knife made of a material harder than bronze, probably iron.[26] The strokes of each character appear blunt and narrow and, most importantly, there are traces of engraving inside each stroke. We can see in the image that the engraver had to cut off the hard bronze bit by bit, leaving repeated chiseling marks that would not have been present had the inscriber worked on a soft clay model, which would have allowed easy carving of long and smooth lines. The repeated chiseling marks are, astonishingly but subtly,

[21]For the translation of the edict, see Sanft, *Communication and Cooperation*, 59.

[22]Name of a county, in today's Shaanxi Pucheng 陝西蒲城. See Chen Peifen, *Xia Shang Zhou qingtongqi yanjiu*, vol. 6, 471.

[23]In today's Shanxi Linxian 山西臨縣. See Chen Peifen, *Xia Shang Zhou qingtongqi yanjiu*, vol. 6, 471.

[24]Chen Peifen, *Xia Shang Zhou qingtongqi yanjiu*, vol. 6, 471. Qiu Guangming and his colleagues mention that Li Xueqin 李學勤 argued that the fifth character should not be read as "shuai" 率. But Qiu Guangming and his colleagues do not give any reason to support this reading. See Qiu Guangming et al., *Zhongguo kexue jishu shi*, 166n1. I follow Wang Hui's decipherment in Wang Hui 王輝, "Pinli de qiyuan jiqi yanbian" 聘禮的起源及其演變, *Qin Shihuang Diling Bowuyuan* 秦始皇帝陵博物院 (2012), 418; he reads the fifth character as "qian" 遣.

[25]See Li, "To Rule by Manufacture," 6; *Zhongguo gudai duliangheng tuji*, 126, no. 180.

[26]Ma Chengyuan, "Jinhou Su bianzhong" 晉侯穌編鐘, in *Jinhou Mudi Chutu Qingtongqi Guoji Xueshu Yantaohui lunwenji* 晉侯墓地出土青銅器國際學術研討會論文集, edited by Shanghai Bowuguan 上海博物館 (Shanghai: Shanghai Shuhua, 2002), 9. An earlier version of this article appears in *Shanghai Bowuguan jikan* 上海博物館集刊, vol. 7, edited by *Shanghai Bowuguan jikan* Bianji Weiyuanhui 《上海博物館集刊》編輯委員會 (Shanghai: Shanghai Shuhua, 1996), 1–17; see also Guan Xiaowu 關曉武 et al., "Jinhou Su zhong keming chengyin shitan" 晉侯穌鐘刻銘成因試探, in *Jinhou Mudi Chutu Qingtongqi Guoji Xueshu Yantaohui lunwenji*, 331–45.

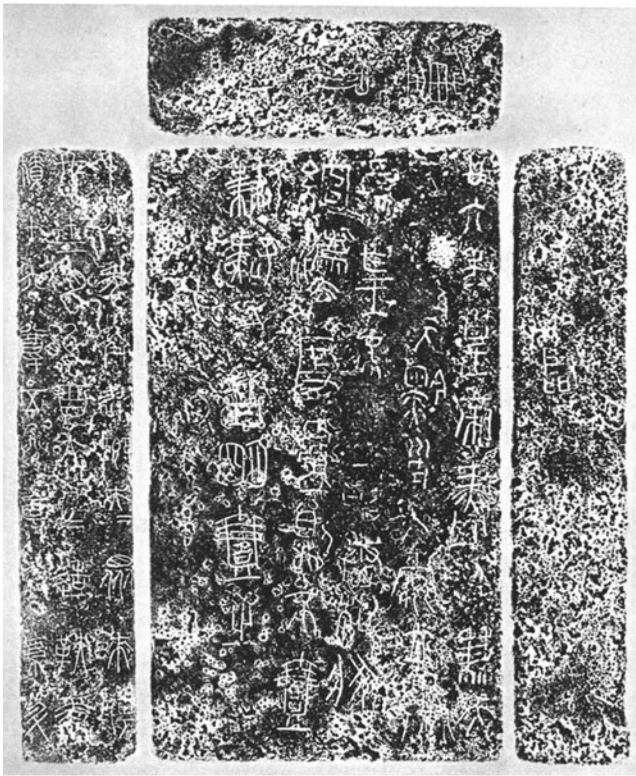

Figure 2. Rubbings of inscription on the “Shang Yang” cuboidal container. After *Zhongguo gudai duliangheng tuji*, 45, no. 81.

Figure 3. (Left) detail of the inscription on the Dagui 大騩 weight. Ca. 221 BCE. Nanjing Museum, accession no. 274. (Center and right) two characters, *ming* 明 and *yi* 壹, of the inscription of Qin Shihuangdi’s 221 BCE edict on the “Shang Yang” cuboidal container. Photographs by the author.

very much visible on the portion of the record of Yang and the capacity of the cuboidal container (Figure 4, center and right).[27] One character in particular, *shi* 十 in the

[27]See Ma Chengyuan, “Jinhou Su bianzhong,” 9.

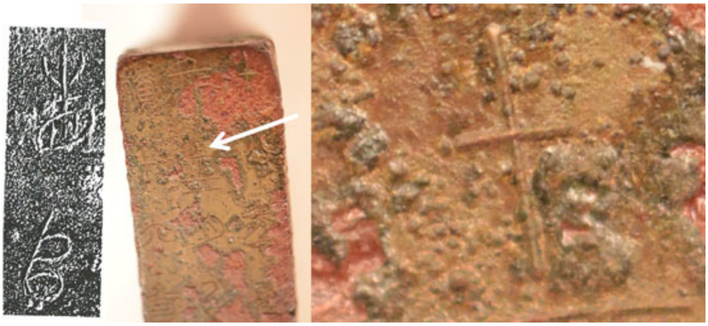

Figure 4. (Left) two engraved characters on one of the Jin Hou Su bells. Ca. 846 BCE. After Ma Chengyuan, "Jinhou Su bianzhong," 16, fig. 2. (Center and right) the "Daliangzao Yang" 大良造鞅 inscription on the "Shang Yang" cuboidal container and detail of one character, *shi* 十 (indicated by an arrow). Photographs by the author.

inscription on the left wall of the container, shows the chiseling marks. This part of the inscription was very clearly engraved rather than cast.

A cast inscription can only be produced at the time of casting, while an engraved inscription is added later. This above-mentioned evidence suggests that the cuboidal container was cast in approximately 221 BCE, while the record of Yang and the volume were engraved later. The current consensus is that the cuboidal container was cast in Yang's time, around 344 BCE.[28] But if the 221 BCE edict was cast on the cuboidal container, it must surely date no earlier than 221 BCE. These observations overthrow the current consensus on the dating of the famous "Shang Yang" cuboidal container, and force us to revisit the history of the development of inscription production in ancient China, and by extension the sequence of container production.

If the cuboidal container was cast, this implies that its producers might have first created a decorated clay model with all inscriptions carved in positive, namely, a decorated model that looked exactly like the finished bronze container.[29] A decorated model with inscriptions carved in positive would have provided the producers with a visually straightforward example to refer to before the final casting. Moreover, the strokes of the characters *ming* and *yi* clearly illustrate that they were first carved on the soft clay model in positive. A clay mold was then packed around the model to absorb all carved, sunken inscriptions. The mold was then sliced into sections, removed from the model, and re-assembled. A clay core was inserted into the re-assembled mold to control the thickness of the walls of the container and its volume.[30] The core had to hold in position and should not join with the outer mold sections; otherwise there would have been defects, more specifically holes, in the final container.

Calculation, Imitation, or Replication?

Two more questions merit further investigation: 1) whether the Qin container casters used the same decorated model to produce multiple identical molds, and 2) whether they used the same core to produce models and molds. If the casters indeed used the

[28]See Chen Peifen, *Xia Shang Zhou qingtongqi yanjiu*, vol. 6, 471.
[29]Bagley, "Anyang Mold-making and the Decorated Model," 39–90.
[30]See Kerr and Wood, *Ceramic Technology*, 401–2.

same model to replicate identical molds, there is a possibility that we can find containers that share the same size, shape, same positioning and execution of characters of inscription, and decorative patterns, if any. If they used the same core to replicate models and molds, that makes a very different story. Containers that share the same core may not be identical in terms of size, shape, and positioning and execution of characters of inscription. But the volume or shape of the cavity, namely the empty sunken parts, of the containers would be identical in terms of size and shape.

Regarding the first question, the casting of bronze weights may serve as one reference point. I have examined over fifty Qin weights and not located a single identical pair.[31] Artefacts cannot be superimposed and compared easily unless they can be turned into 3D virtual models, and I have 3D-scanned some of the weights and provided related images and 3D models of the weights online so that other scholars can make their own comparisons.[32] My finding is that the bronze weights merely appear similar, and their casters likely consulted the designs of some earlier, original, or standard weights, but they did not replicate them.

Distinct from the weight casters' concerns about mass and shape of solid weights, container casters on the other hand attended to the volume of the containers. I have examined and compared two containers, namely the "Shang Yang" cuboidal container and another measure also bearing Qin Shihuangdi's 221 BCE edict (Figure 1, right).[33] Though not identical, their size and shape are highly similar; and the positioning and execution of their inscriptions differ. These observations allow me to conclude that the two containers did not come from the same decorated model, but their volumes are quite similar, about 202 and 216 ml. We know that corrosion and tension over two millennia may have changed the shape and size of the bronze to a certain degree; thus the 14 ml variation is not a significant variation. Qiu Guangming and his colleagues, and the staff of the Shanghai Museum, Shanghai Shi Ceshi Jishu Yanjiusuo 上海市測試技術研究所, and the Shanghai Shi Jiliang Ceshi Guanliju 上海市計量測試管理局 carried out detailed measurements of the rectangular cavities of the two containers and found that their dimensions are very similar ($12.5 \times 7 \times 2.3$ and $12.5 \times 7 \times 2.5$ cm^3).[34]

[31]Li, "To Rule by Manufacture," 22.

[32]See www.makifit.com/bmbw/detail2.html. By 3D scanning of artefacts and making these scans available online, a new approach to the study of art history and archaeology has been invented. Readers' perspectives are limited when viewing 2D images and they cannot either re-examine or validate the original observer's results. But 3D models allow full access to the real dimensions of the artefacts. Scholars can use this tool to validate the original observer's conclusions by repeating the observation process the observer is recorded to have followed and developing their own perspectives as they examine the artefacts in a new light.

[33]The accession no. of the other container, which is also in the Shanghai Museum collection, is 46425.

[34]Qiu Guangming et al., *Zhongguo kexue jishu shi*, 166–68, 179; Chen Peifen, *Xia Shang Zhou qingtongqi yanjiu*, vol. 6, 473. Even though the measuring staff stated that they performed the most scientific measuring of the two containers, variations and errors may still exist because different people may have chosen different points to measure. The two containers were not made to modern standards. Therefore, statistical variations are to be tolerated. See Liu Yanfei 劉艷菲 et al., "Shandong Zoucheng Zhuguo gucheng yizhi xinchu taoliang yu liangzhi chulun" 山東鄒城邾國故城遺址新出陶量與量制初論, *Kaogu* 考古 2019.2, 101n4. They used millet grain to measure the volumes of pottery containers. But measurements at different times also differ. For example, the volume of one of the pottery containers they measured, H404②:18, ranges from 3622 to 3773 ml. See Liu Yanfei et al., "Shandong Zoucheng Zhuguo," 90. They conclude that deformation and restoration of the pottery containers on the one hand, and measurements by different persons at various times on the other hand, are the likely factors leading to these variations. There is one more cuboidal container for comparison. See *Zhongguo gudai duliangheng tuji*, 59, no. 99. It was previously

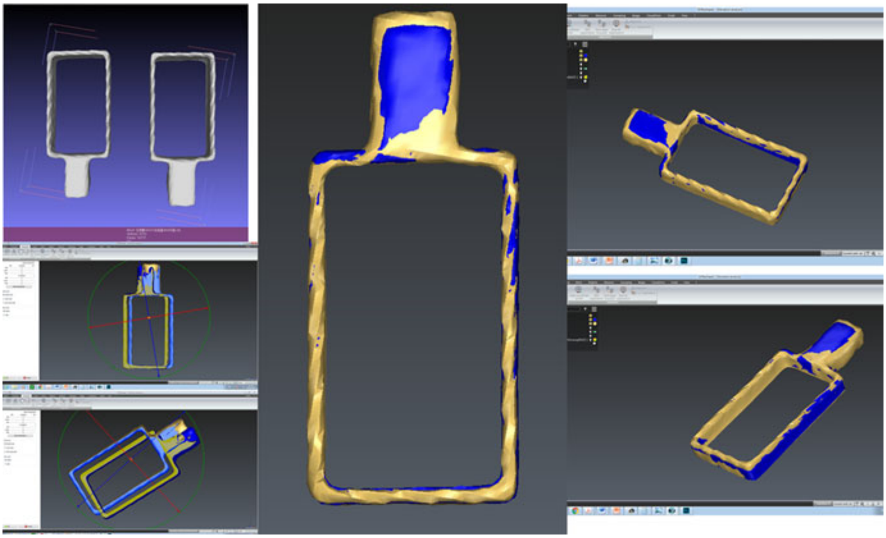

Figure 5. Comparing the cavities of the "Shang Yang" and the Qin Shihuang cuboidal containers. Top left: 3D models of the two containers, processed in Meshlab. We can see that their general shapes are slightly different. Center left and bottom left: attempting to superimpose the cavity of one container upon that of another, processed in 3D Reshaper. Center: finding no mismatch when the cavities of the two containers superimposed. Top right and bottom right: different views of the superimposed containers. Images by the author.

Taking into account the likely corrosion and deformation of the bronzes over time, we can conclude that the two containers share a very similar volume and also have cavities of the same size and shape.

I made a 3D scan of the two containers and superimposed one onto the other in professional 3D computer software (Figure 5).[35] The result confirmed the measurements that the size and shape of their cavities are the same. Theoretically, to achieve the same volumes the rectangular cavities of the two containers do not need to share the same size and shape. For example, if one is 12.5 x 7 x 2.3 cm^3, the other could be 20 x 5 x 2.2 cm^3; their volumes are the same but the shapes of their cavities are different. It seems, however, that at least in this instance the casters of the two containers did not achieve the same volume by calculation. The superimposition result implies instead that they might have referenced from the shape of a standard container, or even shared the same core for their casting.

The shape of a container was determined by the shape of the assembled outer mold sections and the thickness of the metal by the space between the core and the outer mold, while the cavity of a container was determined by the shape and size of its core.[36] The focus of the container casters was always on the volume of the containers. The size and shape of the containers were usually a lesser concern. By sharing the same

housed in the Zhongguo Lishi Bowuguan 中國歷史博物館, which is now called "the National Museum of China." But the National Museum of China did not reply to my request for access to this container. It is recorded that the length of the entire object is also 18.7 cm and its volume is 210 ml. But the dimensions of its rectangular cavity are different: 14.5 x 8.4 x 2.6 (= 316.68) cm^3. A part of the measurement record must be wrong.

[35]The software used is Meshlab (www.meshlab.net/) and 3D Reshaper (www.3dreshaper.com/fr/).

core, or by replicating cores of the same size and shape, the casters could easily and efficiently produce containers sharing the same volumetric standard. One may question the likely factors that might lead to any variation. Since the cores were made of clay, they might shrink to a certain degree during the pouring process when they encountered the hot molten bronze. But casters could bake the cores in advance before inserting them into the molds for casting.[37] Baking the cores makes water evaporate and burns off impurities, thus solidifying, stabilizing, and consolidating the shape and size of the cores, and this significantly reduces the possibilities of shrinkage during the pouring. Casters might well insert baked cores into the molds for casting and thereby reduce the risk of changes to the final volume of the containers. They could also choose a type of clay with a lower degree of contraction. Moreover, casters could also put soft clay into the cavity of an existing container and thereby obtain a clay core that bore the shape and size of the cavity of the existing container. Hence, they could replicate the shape and size of the cavity of almost all containers, and thus replicate the volumes and achieve the same volumetric standard.

Table 2 provides a list of Warring States period and Qin Dynasty containers that provide more interesting clues:

Although I have not examined and 3D-scanned all of these containers in person, the dimensions of their cavities provide interesting clues. We can observe from the images that the containers within each group may not derive from the same decorated models. But their cavities seem to be of a very similar size and shape. Further detailed research would be needed to reach firm conclusions on these issues. Observing the containers from Group 1 to Group 3, we may surmise that the practice of using the same clay cores to produce Qin Dynasty containers sharing cavities of the same size and shape might have developed since at least the Warring States period.

I have not located any use of spacers in any of the objects I have examined; but spacers that were used to sustain the core in the assembled mold, and thereby ensure the thickness of the walls of the containers, were not important. The wall thickness would not affect the volume. If the mold was placed in a fashion that the cavity faced the bottom, the core would be easily sustained and stabilized.

I found a very obvious mold line on the Tianjin bronze elliptical container (Figure 6). This mold line indicates that this container was cast from a mold assembled from separable mold sections. This is evidence of the use of the traditional section-mold casting method on Qin bronze containers.[58] Traditional bronze-casting methods still prevailed. In addition, *surmoulage* containers—those whose molds were created by investing clay around existing bronzes—probably did not exist. The newly cast bronzes would appear very similar to the original ones but they are slightly smaller because

[36]I have been unable to locate any spacer, which would be used to stabilize the distance between the core and outer mold sections, on the two containers. Perhaps the Qin casters did not use a spacer, and instead had some other techniques to stabilize the distance; or alternatively the spacers are covered by corrosion.

[37]Liu Yu 劉煜 et al., "Yinxu chutu qingtong liqi zhuxing de zhizuo gongyi" 殷墟出土青銅禮器鑄型的製作工藝, *Kaogu* 考古, 2008.12, 85–6; Yue Zhanwei 岳占偉 et al., "Yinxu taofan, taomo, nixin de cailiao laiyuan yu chuli" 殷墟陶範、陶模、泥芯的材料來源與處理, *Nanfang wenwu* 南方文物, 2015.4, 158–59; Yue Zhanwei et al., "Yinxu taomo, taofan, nixin de zhizuo gongyi yanjiu" 殷墟陶模、陶範、泥芯的製作工藝研究, *Nanfang wenwu*, 2016.2, 137–40. On the contrary, Rose Kerr and Nigel Wood think that cores needed only to be pressed tight, but not to be fired. See Kerr and Wood, *Ceramic Technology*, 401–2.

[58]Cf. Bagley, "Anyang Mold-making and the Decorated Model," 39–90. But mold lines could have been removed by polishing and may thus not be detectable on every container.

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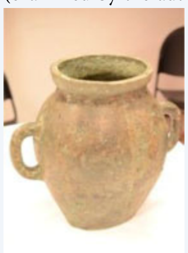
Table 2. List of Warring States period and Qin Dynasty containers that share almost the same volumes and cavities of very similar size and shape.

Warring States period			
Group 1			
Name	Storage/provenience	Dimensions of the entire object (cm)	Volume (ml)
Zi Hezi 子禾子 bronze container[38] 	National Museum of China (NMC); unearthed from Shandong Jiaoxian Lingshanwei 山東膠縣靈山衛 in 1857	Height (h.) 38.5, mouth diameter (d.) 22.3,[39] belly d. 31.8, bottom d. 19	20460
Chen Chun 陳純 bronze container[40] (examined by the author) 	Shanghai Museum; unearthed from Shandong Jiaoxian Lingshanwei in 1857; accession no. 3701	H. 39, mouth d. 23, belly d. 32.6, bottom d. 18	20580

[38]*Zhongguo gudai duliangheng tuji*, 41, no. 78.

[39]The measurers use the Chinese character "jing" 徑, referring to the circular mouths, bellies, and ring feet of the Zi Hezi and Chen Chun bronze containers. I take it as referring to their *zhijing* 直徑 (diameter).

[40]Photo by the author. See also *Zhongguo gudai duliangheng tuji*, 42, no. 79.

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Group 2

Name	Storage/provenience	Dimensions of the entire object (cm)	Volume (ml)
"Great Ying Storehouse" ("Ying dafu" 郢大府) bronze container[41] 	Exhibition Center at the Fuyang District in Anhui (安徽阜陽地區展覽館); unearthed from Anhui Fengtai 安徽鳳台 in 1976	H. 12.5, mouth d. 11.6	1110
Bronze container bearing the inscription "king" ("wang" 王)[42] 	Huainan Municipal Museum (淮南市博物館); unearthed from Anhui Huainan 安徽淮南 in 1957	H. 11.7, mouth d. 12	1125
Zhujiaji 朱家集 bronze container[43] 	Anhui Provincial Museum (安徽省博物館); unearthed from Anhui Shouxian Zhujiaji 安徽壽縣朱家集 in 1933	H. 12, mouth d. 12	1140

[41] *Zhongguo gudai duliangheng tuji*, 55, no. 93.

[42] *Zhongguo gudai duliangheng tuji*, 56, no. 94.

[43] *Zhongguo gudai duliangheng tuji*, 56, no. 95.

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Group 3			
Name	Storage/provenience	Dimensions of the entire object (cm)	Volume (ml)
Yangcheng 陽城 ceramic container A[44] 	Henan Provincial Museum (河南省博物館), unearthed from an ancient iron foundry site at Henan Dengfeng Gaocheng Gu Yangcheng 河南登封告城古陽城 in 1977	H. 10.9, mouth d. 16.7	1690
Yangcheng ceramic container B[45] 	Same as above	H. 10.7, mouth d. 16.7	1690

[44]*Zhongguo gudai duliangheng tuji*, 47, no. 84.
[45]*Zhongguo gudai duliangheng tuji*, 48, no. 85.

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Qin Dynasty			
Group 4			
Name	Storage/provenience	Dimensions of the entire object (cm)	Cavity (cm^3)
"Shang Yang" cuboidal container[46] (examined by the author; Figure 1, left)	Shanghai Museum, accession no. 44331	Length (l.) 18.7	12.5 x 7 x 2.3 = 202.15
Qin Shihuang cuboidal container[47] (examined by the author; Figure 1, right)	Same as above, accession no. 46425	L. 19	12.5 x 7 x 2.5 = 215.65
Group 5			
Name	Storage/provenience	Dimensions of the entire object (cm) and weight (g)	Cavity (cm^3) or volume (ml)
Wucheng 武城 bronze elliptical container[48] 	NMC	L. 24.3, h. 4.8	No capacity record [the *Zhongguo gudai duliangheng tuji* catalogue mentions the dimensions of the cavity, l. 16, width (wid.) 8.3 cm; it is difficult to estimate its capacity because it is in an elliptical shape); 485 ml

[46]*Zhongguo gudai duliangheng tuji*, 44, no. 81.

[47]*Zhongguo gudai duliangheng tuji*, 58, no. 98.

[48]*Zhongguo gudai duliangheng tuji*, 60, no. 100.

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Qin Shihuang bronze elliptical container[49] 	NMC	L. 20.5, h. 5.5	(l. 15.6, wid. 9.5 cm); 495 ml
Tianjin 天津 bronze elliptical container[50] (examined by the author) 	Tianjin Municipal History Museum (天津市歷史博物館), now called the Tianjin Museum 天津博物館, accession no. QWJ972	L. 24.6, h. 4.8	(l. 17.8, wid. 9.8 cm); 490 ml
Lüshun 旅順 bronze elliptical container[51] (examined by the author) 	Lüshun Museum (旅順博物館), accession no. 1.1660	L. 20, h. 6.4, weight 1770 g	(l. 15, wid. 9.2 cm); 490 ml

[49] *Zhongguo gudai duliangheng tuji*, 61, no. 101.

[50] Photo courtesy of the Tianjin Museum. *Zhongguo gudai duliangheng tuji*, 62, no. 102.

[51] *Zhongguo gudai duliangheng tuji*, 63, no. 104.

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Jilin 吉林 bronze elliptical container[52] (examined by the author) 	Jilin University Museum of Archaeology and Art (吉林大學考古與藝術博物館), accession no. 2–484	L. 21.6, h. 6.1, weight 1948 g	(l. 16.3, wid. 8.8 cm); 500 ml

Group 6

Name	Storage/provenience	Dimensions of the entire object (cm)	Cavity (cm^3) or volume (ml)
"Two-edicts" bronze elliptical container A[53] 	NMC	L. 30.2, h. 9.4	(l. 23, wid. 14.6 cm); 1980 ml
"Two-edicts" bronze elliptical container B[54] 	NMC	L. 30.3, h. 9.85	(l. 25.3, wid. 16.4 cm); 2050 ml

[52]Photo by the author. *Zhongguo gudai duliangheng tuji*, 64, no. 105.

[53]*Zhongguo gudai duliangheng tuji*, 66, no. 107.

[54]*Zhongguo gudai duliangheng tuji*, 67, no. 108.

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Group 7

Name	Storage/provenience	Dimensions of the entire object (cm)	Cavity (cm^3) or volume (ml)
Zouxian 鄒縣 ceramic container (Shandong)[55] 	Shandong Provincial Museum (山東省博物館); unearthed from Shandong Zouxian	H. 8	(mouth d. 16.8 cm); 1000 ml
Zouxian ceramic container (NMC)[56] 	NMC; unearthed from Shandong Zouxian in 1950	H. 8.3	(mouth d. 16.4 cm); 970 ml
Palace Museum ceramic container[57] 	Palace Museum (故宫博物院); probably unearthed from Shandong Zouxian	H. 7.8	(mouth d. 16.4 cm); 990 ml

[55]*Zhongguo gudai duliangheng tuji*, 68, no. 109.

[56]*Zhongguo gudai duliangheng tuji*, 69, no. 110.

[57]*Zhongguo gudai duliangheng tuji*, 70, no. 111.

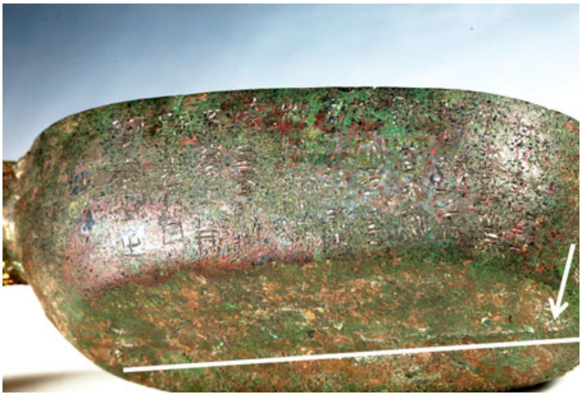

Figure 6. Mold line on the Tianjin bronze elliptical container, indicated by an arrow, along a straight line. Ca. 221 BCE. Tianjin Museum, accession no. QWJ972. Photo courtesy of the Tianjin Museum.

bronze shrinks as it cools. The shrinkage of the *surmoulages* would reduce the volume of the *surmoulage* container as compared to that of the original container, and the *surmoulage* technique is thus unsuitable for making measuring containers.

We have now established that the casters of the "Shang Yang" and Qin Shihuang cuboidal containers (Group 4, Table 2) might have shared the same core, or replicated the cores, in order to produce the cavities of the containers to maintain a standard volume and achieve an accurate and precise measurement. This implies that the Qin casters probably did not need to make careful calculations to measure volumes of containers. They could simply replicate or imitate the cores of standard containers and achieve the same volumetric standards. These hypotheses thus delineate a simple yet efficient method of attainment of accuracy and precision. This will eventually lead us to the larger question of what is really meant by the unification of the measurement systems of the Qin empire.[59]

Bronze Being the Material for Establishing Standards

Currently we have two types of containers, made of either bronze or pottery. In past decades very few of them were archaeologically excavated but some were unearthed in Shandong Zouxian (Group 7, Table 2).[60] Recently, more pottery containers were excavated from the same place.[61] Scholars who have researched these finds have provided the volume data on the Zouxian pottery containers; but they have not considered whether the containers would have shared the same clay core as a means of ensuring efficiency of capacity.[62] Further research is needed to determine the production methods for the pottery containers.[63]

[59]I do not focus on the forms of production control in this article. For a discussion of this issue, see Li, "To Rule by Manufacture." Since we do not have enough examples of archaeologically excavated Qin bronze containers, it is relatively difficult to reach a definite answer.

[60]Qiu Guangming et al., *Zhongguo kexue jishu shi*, 183.

[61]Qiu Guangming et al., *Zhongguo kexue jishu shi*, 183.

[62]It is stated in the catalogue that the inscriptions on the Zouxian ceramic containers were stamped. See *Zhongguo gudai duliangheng tuji*, 68–71. In order to determine whether the Zouxian containers might have

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The dominant material for establishing volumetric standards was bronze. The material choice constituted one of the essential concerns of the Qin bureaucrats. Whilst pottery containers can be very durable when handled with due care, in other circumstances pottery is considerably more fragile than bronze. Low porosity might be another significant factor favoring bronze. The beautifully executed inscriptions of the imperial edicts were also more prominent on bronze than on pottery. As long as neither pottery nor bronze containers deform, and there is no defect on the cast containers and no hole in the pottery ones, either material can create excellent vessels to maintain the volumetric standard; but bronze obviously ranked higher than pottery.

Design Origins of the Measuring Containers

The design origins of the Qin measuring containers are worth examining. My investigation of the design origins of the Qin weights reveals that they had close association with pottery jars from southeastern China and bronze bells.[64] This is a new field of research tracing the artistic references the Qin producers consulted. The artistic associations between the measuring containers and earlier pottery vessels, bronze measuring cups, *dou* 斗, *shao* 勺, *jue* 爵, and other vessels may be revealing when we find more examples. These vessels differed from the measuring containers in function, nevertheless, their shape and decorative patterns were designed with similar concerns. Scraping the inner walls of the bronze measuring containers, if any, would adjust the volume of the containers, which might have been a skill inherited from casters in charge of post-processing and polishing of earlier bronze vessels. I believe that these pursuits of the origins of techniques and designs will help illustrate a world of artistic relationships unknown to previous scholars.

Conclusion

This article provides a fresh perspective on the history of technology in ancient China. We can look into how standard settings of accuracy and precision contributed to the development of technology in the Qin empire. Investigating the foundations of all grand projects of the Qin empire involves the study of the so-called "unification of the measurement systems" because accurate and precise measurement was essential for the success of these projects. I have paid particular attention to how the measuring containers were produced. This study contributes to understanding how Qin bureaucrats utilized these actual, physical objects to define the concepts of accuracy and precision.

We now have better knowledge about the production of measuring containers and the methods used to inscribe characters on bronzes. Most of the extant measuring containers were made of bronze, and were produced with a variety of methods, in which

been produced by the same workshop, we would want to check whether the stamped characters on one container are identical to the corresponding characters on another container. This would entail the application of 3D scan and display technology, because the container walls on which the inscriptions were stamped are curved. We can flatten the 3D models of the inscriptions and superimpose one upon another to determine whether they are in fact identical. Freely moving and rotating the 3D models enable us to compare carefully without being restrained by any museum regulations.

[63]See Liu Yanfei et al., "Shandong Zoucheng Zhuguo," 89–104.

[64]Li, "The Design Origins."

replicating clay cores to produce containers with identical capacity seemed to be an efficient and most feasible method. This article thus enhances our understanding of how Qin producers cast bronzes that served as measuring standards.

The regulation of measurement systems and the technological methods used to establish standards of accuracy and precision are a burgeoning field in the broader realm of world history, and it has received attention from historians of civilizations other than China.[65] The history of the creation of the international metric system in the nineteenth-century France is also well-studied, for example.[66] Accordingly, this article contributes to this area of world history, and a fruitful comparison for the future may lie in contrasting the Qin empire with ancient Mesopotamia and France in the nineteenth century in order to examine how different regimes established standards and attained accuracy and precision with multiple technological means.

This article has also demonstrated the usefulness of incorporating advanced technologies, such as 3D modeling, in examining the production traces of Qin measuring containers. Artefacts can be superimposed upon one another only using virtual technology. It is challenging to confirm replication between two objects with seemingly identical shapes and designs, which are stored in different museums. 3D models of objects with seemingly identical shapes and designs will prove the best virtual models for comparison for the purposes of displaying whether said objects share exactly the same shape, or whether they merely appear similar. Few scholars have applied this methodology to the field of the history of technology in China.[67] It is to be hoped that the demonstration in this article will generate new avenues of development in the burgeoning discipline of digital humanities.

[65]See Robert Tavernor, *Smoot's Ear: The Measure of Humanity* (New Haven: Yale University Press, 2007); Simon Winchester, *The Perfectionists: How Precision Engineers Created the Modern World* (New York: Harper, 2018); Robson, *Mathematics in Ancient Iraq*.

[66]Robert A. Nelson, *SI: The International System of Units* (Stony Brook: American Association of Physics Teachers, 1982); O.W. Van Assendelft, "The International System of Units (SI) in Historical Perspective," *American Journal of Public Health* 77.11 (1987), 1400–1403, www.ncbi.nlm.nih.gov/pmc/articles/PMC1647091/; Alder, *The Measure of All Things*; Quinn, *From Artefacts to Atoms*; Bureau International des Poids et Mesures, *The International System of Units (SI)*, 8th edition (Paris: Organisation intergouvernementale de la Convention du Mètre, 2006), updated in 2014, English version, 93–180, retrieved on September 10, 2018 from www.bipm.org/utils/common/pdf/si_brochure_8.pdf; Edmund Isakov, *International System of Units (SI): How the World Measures Almost Everything, and the People Who Made It Possible* (New York: Industrial Press, 2014).

[67]See Andrew Bevan et al., "Computer Vision, Archaeological Classification and China's Terracotta Warriors," *Journal of Archaeological Science* 49 (2014), 249–54.

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