Recreating the Pulsilogium of Santorio: Outlines for a Historically-Engaged Endeavour

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Abstract

Between 2015 and 2016 a series of seminars on the history of early modern technology and medicine were held at the Centres for Medical History and Biomedical Modelling and Analysis of the University of Exeter. As a result of that work we laid down the basis for the first historically accurate reconstruction of a seventeenth-century instrument, the *pulsilogium* of Sanctorius (1561-1636). Previous copies were in fact either simple models for display or lacked any commitment to historical accuracy. This short contribution explores some of the results we obtained from the recreation of this device and experiments we recreated which shed new light on the early application of the pendulum as a scientific instrument. A fuller and much more detailed account of these discoveries will be given in a forthcoming contribution edited by Filip Buyse for a special issue of the *Journal of Social and Political Science*.

1. Santorio and the Emergence of Early Modern Science

The emergence of modern science between the sixteenth and seventeenth century had in medicine an important field of development, thanks especially to the work of Santorio Santori (1561-1636) (Fig. 1).

Mostly known for his contribution to the study of metabolism, Santorio developed or invented several types of instruments, among which was a device named *pulsilogium* (literally: 'an instrument that measures the pulse') which represents the first application of the pendulum to physiology and the first instrument of precision in the history of medicine. The earliest known

Fig. 1 *Santorio Santori (1561-1636). Portrait from the* Opera Omnia *in four volumes (Venice 1660).*

mention and possible application occurs in 1602 as part of a book on the pulse (*De pulsibus*) written by a colleague of Santorio in Padua. It probably constituted a source of inspiration for, rather than being an invention by Galileo, and sparked an entire path of experiments in seventeenth-century Europe. Santorio presented his inventions as rough engravings in his *Commentaria in Primam Fen Primi Libri Canonis Avicennae* ('Commentary to the Canon of Avicenna' - Venice 1625) promising soon to publish another book called *De instrumentis medicis* ('On Medical Instruments'): a task that, unfortunately, he was not able to accomplish during his life. Consequently, many descriptions related to his instruments are partial or too general. Moreover, previous attempts at reconstructions have subsequently been found to be either not historically informed or in some cases completely misleading. From this standpoint, the reconstruction of Santorio's instruments represents an essential task for any historian or philosopher of science.

Relying on a new assessment of Santorio's works as a whole, as well as on experimentation and in some cases on new documentary proofs, we were able to define some key principles that laid down the basis for the first historically accurate reconstruction of Santorio's *pulsilogium* (Fig 2a-b).

1.1 Background

Experiences with, or referring to the pendulum, have a long history in science, being notably witnessed in the works of Nicole Oresme (1320-1382), Giovanni Marliani (end of 15^{th} century), Leonardo da Vinci (1452-1519), Gerolamo Cardano (1501-1576), and Giovanni Battista Benedetti (1530-1590).[1] Galileo's famous studies on the pendulum, started at around the ninth decade of the sixteenth century, would not lead to any serious outcome until well after 1602. Galileo himself, in fact, seems not to be making any practical use of such a device up to the time of publication of his *Discorsi e dimostrazioni matematiche intorno a due nuove scienze* ('Two new sciences', 1638).

Like Galileo, contemporary astronomers and physicians were concerned with the

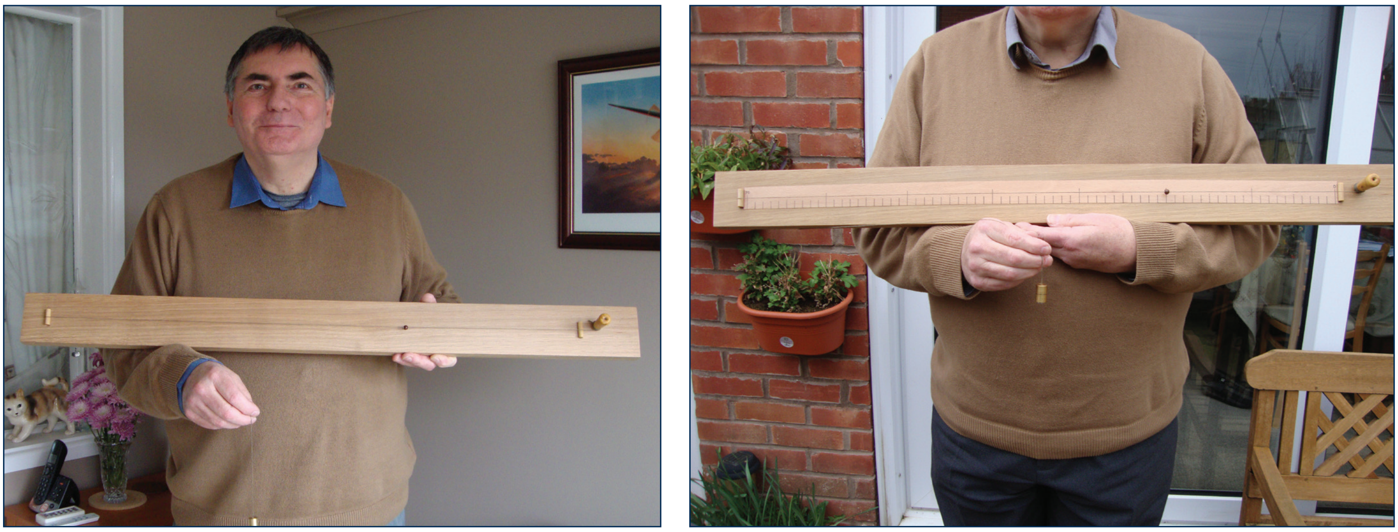

Fig. 2a-b *David Taylor and the Recreation of 'Pulsilogium A2' (January 2016).*

Fig. 3 Quadrans Muralis seu Tichonicus *from Brahe,* Astronomiae instauratae mechanica *(Nuremberg 1602).*

problem of attaining an exact measurement of time.

In the frontispiece of his *Astronomiae instauratae mechanica* (Nuremberg 1602), for instance, Tycho Brahe (1546-1601) displays his endeavours to obtain a precise value of the time elapsed in his astronomical observations by measuring and registering the results provided by three different types of wall clock in attempts to compensate for the notorious lack of reliability of mechanical devices (Fig. 3). Unlike Brahe, Johannes Kepler (1571-1630) still considered the pulse's record as a reliable timekeeper for astronomical observations, and tried to assess the number of pulse strokes per minute by using those of a healthy man at rest.[2] Such a calculation, however, is not pursued by adopting any precision device and accordingly it fails to consider fluctuations of the pulse frequency that are a consequence of the slightest change due to environmental factors and/or psychological conditions in the patient. The solution to this problem came, much earlier, from the field of medicine and was due to the work of the Italian physician Santorio Santori (1561-1636).

2. Functioning and Purpose

At first Santorio seemed to introduce the pendulum to discriminate between regularity and irregularity and record the pulse frequency. For this he invented a series of devices of increasingly complex design meant to convert vital parameters into measure (see Figs 4-8), which for our purpose we have classified according to letters and numbers [TABLE 1]. In his first description – dated 1603 – Santorio states that an instrument he invented and which he called *pulsilogium* was able *'to show all the differences in equal movements'* that is to say that it could mark equal intervals of time.[3] Although, it was only in 1625 that Santorio would reveal that such an instrument was pendulum regulated, there can be little doubt that it was the same instrument used by him since 1602. Even though the exact theoretical path lying behind Santorio's studies on the pendulum remains uncertain, Santorio's remarks prove that he had identified correctly the fundamental property of the pendulum which allowed him to painstakingly collect, record and compare various data resulting from the measurement of the pulse. In the simplest of his devices (Fig. 4), by suspending a leaden ball over a graduated bar, the physician had only to synchronise the swing of the pendulum with the frequency of the pulse, take note of the result and subsequently compare it with previous records. In a slightly improved version of the same device (Fig. 5) the same measurement is achieved by using a horizontal beam at one end of which a tapered peg controls movement of the linen thread; a small wooden bead fixed to the thread indirectly indicates pendulum length on a scale engraved onto the beam.

Santorio or Galileo?

All the scholars who dealt with Galileo and his studies on motion, simply assumed that Santorio's *pulsilogium* was a direct outcome of the former's research into the properties of the pendulum. Unfortunately, there are many major problems with this hypothesis. The most important of which is

Table 1

CLASSIFICATION OF SANTORIO'S PULSILOGIA

A or *Beam type*	1	The beam is divided in 80 degrees
	2	The beam is divided in 70 degrees [not marked only displayed]
B or *Dial type*	1	The dial is divided in 12 degrees
	2	The dial is divided in 24 degrees
C or *Pocket watch type*		Provided with 7 divisions (*differentiae*) + 7 subdivisions (*minuta*)

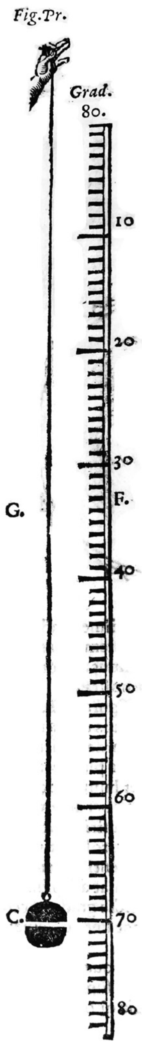

Fig. 4 *Pulsilogium Type A1.*

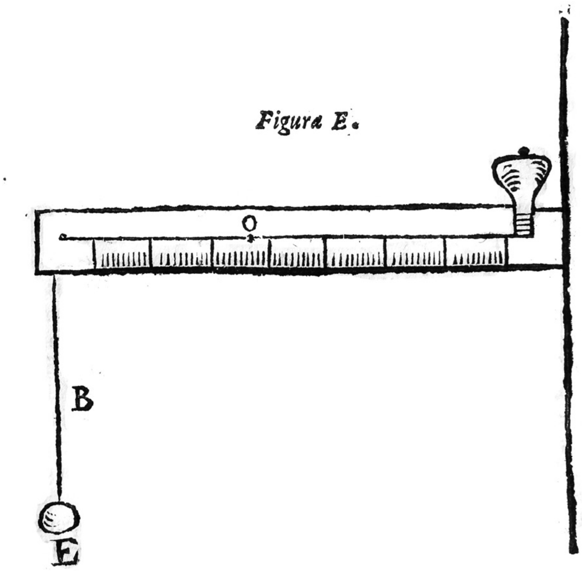

Fig. 5 *Pulsilogium Type A2.*

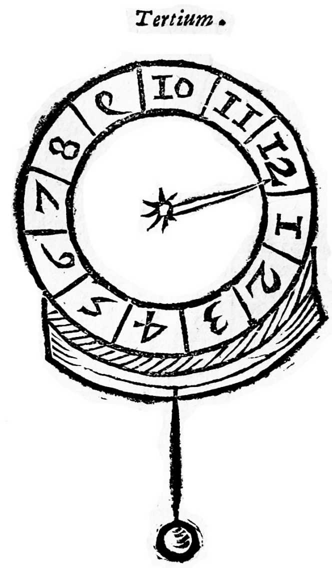

Fig. 6 *Pulsilogium Type B1.*

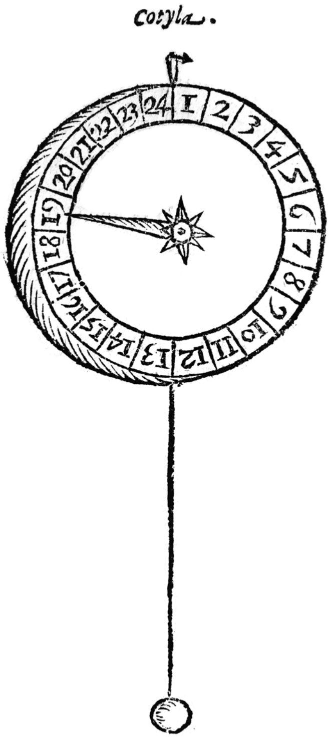

Fig. 7 *Pulsilogium Type B2.*

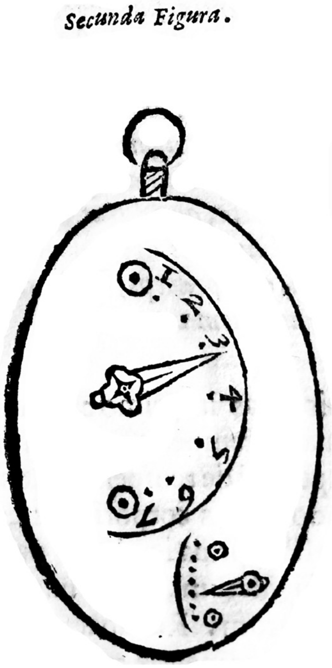

Fig. 8 *Pulsilogium Type C.*

that it takes no account of Santorio's words and further assumes the primacy of Galileo's over Santorio's studies that is historically groundless.

In his research, Dr Bigotti found that the first quote referring to Santorio's *pulsilogium* was published in Padua in 1602 at the time in which Galileo was teaching mathematics there. The book, published by a colleague of Santorio, the physician Eustachio Rudio from Belluno (1548-1612) announced the creation of an instrument by Santorio in a few words that are amplified in Santorio's account a year later. In 1603, in fact, Santorio published his own description which revealed that he had already had enough time to experiment extensively with his instruments and had found at least 133 specific differences related to the pulse, a detail that – coupled with Rudio's description – suggests a much earlier development of the *pulsilogium*, possibly between 1590 and 1600. Galileo, on the other hand, refers to his experiments on the pendulum in a letter dated November 1602 to Guidobaldo del Monte (1545-1607), but does not suggest any practical application for it, as – and this is essential to our understanding of Galileo's studies – he had not found a mathematical proof for the isochronism of the pendulum. He refers to having performed experiments (*esperienze*) and describes a mere mechanical explanation (*senza trasgredire i termini della meccanica*) for his observations.[4] In all likelihood, Galileo's experiments were reawakened by Rudio's announcement of the new possibilities opened up by Santorio's invention although the latter, in turn, had certainly benefited from the meetings held in Venice and Padua at the circles of Gian Vincenzo Pinelli (1535-1601) and Andrea Morosini (1558-1618), which Galileo also partook and many mathematical arguments were discussed. As a final point, whilst Galileo never personally claimed the invention of such an instrument – it was indeed his disciple Vincenzo Viviani (1622-1703) who claimed it on behalf of him some fifty years later – Santorio openly ascribed that invention to himself in all his works. All the early historical records found on experimentation linked to the *pulsilogium* – most notably the experiments of Isaac Beeckman (1588-1637) on the pendulum and Peter Lauremberg's (1585-1639) replica of this device – acknowledge Santorio as its inventor. Finally, it must be remarked that:

The invention of the *pulsilogium* perfectly fits in Santorio's programme for quantification in physiology and with the invention of other instruments, such as thermometers and hygrometers, following a threefold method of empirical analysis as:

a) measurement of a physiological process through definite parameters;

b) designing and manufacturing devices to use to guarantee certainty in measurement;

c) essential part of repeated and controlled experimentation.

Regrettably, the hypothesis of Santorio's dependence on Galileo's studies led scholars to completely neglect the direct reading of Santorio's works, notoriously bulky but nonetheless revealing of a different approach to the use of the pendulum.

What Does the Pulsilogium Measure?

According to the statements we have collected from Santorio's works and other historical testimonies, the *pulsilogium* is intended to measure 'the quantity' or 'the degree of distance' (*quantitas/gradus recessus dimetiri*) of the pulse rate, that is to say its variation in healthy or unhealthy conditions. Such distance (*recessus*) spans from a *minimum* to a *maximum* of frequency as well as intensity which, in reference to the latter, Santorio – and all Renaissance physicians – called 'range of health' (*latitudo sanitatis*). The *pulsilogium* seems to have been used chiefly as a comparator: Santorio compared different segments of chord related to the increase or decrease of the pulse rate in terms of a rapport between degrees. He adopted the device as especially revealing of the variation of pulse frequency in fevers and other symptoms. Santorio further specifies that unaided by use of his *pulsilogium* such a variation can be so small that even a well-trained physician can fail to perceive it, thus getting a terribly wrong diagnosis.

Santorio's appreciation of quantitative values associated with physiological/pathological conditions is particularly relevant as it indicates that this physician sought after objective criteria and understood the various conditions of the body as dynamic states varying within a range *(latitudo)* susceptible to measurement.

Inasmuch as measuring the degree of the pulse, or rather its *latitude*, is something different from measuring directly the pulse rate, the kind of measurement Santorio was capable of achieving with his instrument needs some further explanation – in particular his use of terms such as 'distance' and 'degree'.

The terminology stretches back to the scholastic theory of the 'latitude of forms' (*latitudo formarum*) that had a long-lasting tradition in medicine where – from Galen onwards – the concept of degree was pivotal in understanding the action of drugs and temperaments on the body. In keeping with both of these theories (degrees and latitude), Santorio regarded the normal activity of a body as a series of qualitative changes comprehended between a minimum and maximum of intensity that could be measured by means of an incremental scale of degrees. It is worth noticing that, before Santorio, the degree of intensity related to each state was proportional to the individual under scrutiny thus being completely arbitrary.

One of the major scientific achievements of Santorio, in the history of science and ideas, was the ability to convert the concept of degree into a quantitative value by means of instruments devised for the purpose.

As shown above, the *pulsilogium* fits exactly within this framework. As we will show in another contribution, the fact that the disposition of degrees in the *pulsilogium* is consecutive, the measurement linear and the difference between the minimum and maximum results in 80 degrees (see Fig. 4), are not casual details, they highlight the fact that:

a direct reading of the pulse frequency in beats per minute would not be possible, as the pulsilogium only allows the user to explore it in terms of linear progression. It is worth noticing, however, that for the sake of medical diagnosis, a direct reading was also useless and could remain unknown to the physician: the exact record of the degree is for all practical purposes a sufficiently reliable means of monitoring the inclination towards health or sickness in each patient.

Whether by means of the *pulsilogium* Santorio pursued an analysis of his patients grouping them by typology (melancholic, bilious, choleric, phlegmatic constitution) remains unclear, yet his constant use of the plural for referring to his subjects (*sani/aegri homines*) is possibly revealing of such an eventuality. What we can take for granted however is the fact that experiments with the *pulsilogium* were repeated, due to the chiefly comparative use of the instrument: indeed Santorio used it to define the range of the normal/physiological activity of the body which entails a painstaking and repeated measurement of the pulse, over long periods of time and under different environmental conditions.

3. Preparations for the Replica

In preparation for our replica we collected and carefully analysed Santorio's writings and compared them with the available replicas in various museums of Europe. Discussion of the historical references took place also in the form of public seminars organised by Dr Jo Welsman (Centre for Biomedical Modelling and Analysis – Exeter). In its final form, the instrument – based on the best-known model depicted in 1625 which we defined in our general classification as A2 – was the result of two rather intense years of research by Fabrizio Bigotti and David Taylor, spent in analysing materials, scale, reliability and limitations of the instrument and, for each modification or improvement, discussing the overall concept of measurement underpinning the new solution adopted.

Materials have been carefully chosen by relying on contemporary documentation of Venetian furniture and, although not directly affecting the isochronous swing of the pendulum, dimensions of the oscillating ball received considerable attention as well. Allowing that the *pulsilogium* could be used also as a portable instrument, the adoption of heavy and bulky material would have been unlikely. As such, David Taylor suggested that Santorio's original most probably used a musket ball as its pendulum bob. This suggestion was based on archaeological evidence of musket shot in use in 17th century Europe, and on the relative scale of components in the woodcut image (see Fig. 5). However, to comply with the current *Health and Safety* regulations - in particular with COSHH (Control of Substances Hazardous to Health) and CLAW (Control of Lead at Work) – rather than lead, as in Santorio's original description, we were constrained to use iron or brass as its material.

Scale units and measurement resolution were pivotal to understand the functioning and application of the *pulsilogium*, and to this very aspect – which seems to have prevented scholars from achieving any positive result about Santorio's methods hitherto – we devoted most of our energies. The final outcome of our research will be presented and discussed at length in the forthcoming volume *Oscillating Pendulum and the swinging philosophy of the seventeenth century* a special issue of the *Journal of Social and Political Science* edited by Filip Buyse. For readers of the 'SIS Bulletin' we can nevertheless anticipate that, after much discussion on how to approach the question, the ultimate answer came from the descriptions we collected, and especially from the fact that all of Santorio's instruments deal with equal intervals of ten divisions over a linear scale.

Similarly, dimensions of the beam in the *pulsilogium* A2 was an unknown that we strove to understand and solve. The problem was tied up with the overall measurement resolution of the instrument and the physiological range of its application; that being the case we decided to start from normal range of 60 to 100 beats per minute, the device being used by Santorio especially to assess the physiological conditions of the body. The resulting overall length of the instrument scale is then 64.3cm, adding the space required to fit the tapered peg and other components the overall beam length comes out at about 76cm. These aspects and others related to Santorio's improvements on different models of *pulsilogia* will be explored and discussed in the forthcoming contribution.

3.1. How Reliable is a Pulsilogium?

How reliable was the *pulsilogium* in terms of actual measurements? This question was addressed in a series of experiments conducted by Dr Joanne Welsman and David Taylor at the South Devon University Technical College of Newton Abbot (UK). Students with no background in early modern medicine, were asked to carry out measurements using replicas of Santorio's *pulsilogium* A2. Measurements were taken in a kind of doctor patient session, whereby two different students (doctors) were asked to use replicas of *pulsilogium* A2 to match the pulse rate of a third one (the patient) and record the measurement obtained. As expected, a slight increase or decrease of pulse rate due to environmental or psychological factors in the 'patient' was seen, overall however, it turned out that the difference in measurement was negligible and almost exclusively attributable to the ability of each observer.

Conclusions

When we originally began our research and experiments into Santorio's *pulsilogium*, the common opinion according to which, in his early years in Pisa while studying medicine, Galileo had invented an instrument to allow the exact record of the pulse frequency, was still standing. As one result of our research, this view, already debated but never seriously challenged by historians, can now be dismissed. Our recreation of Santorio's *pulsilogium* A2 demonstrates that the first technological application of the pendulum is due to Santorio and it was already known before 1602. As a medical instrument the *pulsilogium* allowed physicians to record the 'latitude of the pulse', not its exact frequency in terms of beats per minute, that is to say the range of variation of the pulse in both normal or pathological condition and so to compare data collected over time. Combined with other historical evidences that will be discussed in the forthcoming contribution, our research refutes the direct involvement of Galileo in the creation of the *pulsilogium* and places its development in the context of late Aristotelian physics, whereby motion and velocity were measured not in terms of rapports between magnitudes - as Galileo will do much later - but in terms of degrees that were added or subtracted by an already known quantity. Indeed, with the *pulsilogium* of Santorio we are still in an intermediate phase in which natural philosophy was crossing the boundaries of the abstract generalisation provided by the medieval physics to access the realm of number and quantification; a phase which represents the essential pre-requisite of Galileo's studies, not their outcome. Such a transition was first made within the context of Late Renaissance medicine and natural philosophy in a moment in which a new approach to nature was shaped. Thus, one of the major outcomes of our research is that it potentially provides a new insight on the concept of quantification in medicine and, most notably, on the functioning of early modern technology: Santorio's *pulsilogium* marks not only the opening era of precision instruments in early modern science, but represents the first fundamental step towards the shaping of modern experimental physiology.

Acknowledgements

The archival research on Santorio's instruments was originally supported by the SIS Grant awarded in 2014 to Dr Fabrizio Bigotti and has been supported thereafter by the Wellcome Trust as part of a major project on quantification in medicine aimed at classifying, understanding and recreating all of Santorio's instruments for physiological and physical measurement (106580/Z/14/Z). The reconstruction of Santorio's *Pulsilogium* (Type A2), however, is very much a team effort and was part of the engaged research project *The Laboratory of Santorio* held at the University of Exeter – Centres for Medical History and Biomedical Modelling and Analysis. Finally, we would like to express our gratitude to Prof. Jonathan Barry, Co-director of the Centre for Medical History, for his constant and unconditioned support throughout the project duration.

Notes

1. A comprehensive history of the use of the pendulum before Galileo is still missing. For a general overview the reader could consult Renn 2001 and Büttner 2008.

2. Kepler 1618, vol. I, bk 3, ch. 3, pp. 278-279: 'In homine valente, robusto et perfectae aetatis, complexionis melancholicae aut consenescente fere singulis secundis existunt singuli pulsus arteriae (60°), nullo discrimine inter systolen et diastolen: ita essent in uno minuto pulsus sexaginta; sed rara est haec tarditas, vulgariter numerantur 70, in cholericis et feminis 80, quatuor in terna secunda. Breviter in una hora quatuor millia plus minus'.

3. Santorio 1603: 109rD-109vB.

4. Drake 1979: pp. 69-71.

References

Bedini 1991: Silvio A. Bedini, *The Pulse of the Time*. Galileo Galilei, the determination of longitude, and the pendulum clock (Florence: Leo S. Olshcki Editore, 1991).

Büttner 2008: Iochen Büttner, *The Pendulum as a Challenging Object in Early Modern Mechanics*, in Walter Roy Laird and Sophie Roux (Eds), *Mechanics and Natural Philosophy before the Scientific Revolution* (Dordrecht: Springer, 2008), pp. 223-238.

Castiglioni 1920: Arturo Castiglioni, *La vita e l'opera di Santorio Santorio Capodistriano* (Bologna: Licinio Cappelli, 1920).

Caverni 1891-1900: Raffaello Caverni, *Storia del Metodo Sperimentale in Italia* (Florence: Stabilimento G. Civelli Editore, 1891-1900).

Drake 1969: Stillmann Drake, 'Galileo's 1604 Fragment on Falling Bodies', *The British Journal for the History of Science*, 4-4 (1969), pp. 340-358.

Drake 1979: Stillmann Drake, *Galileo at Work. His Scientific Biography* (Chicago and London: The University of Chicago Press, 1979).

Ettari-Procopio 1968: Maria Stella Ettari and Marco Procopio, *Santorio Santorio. La Vita e le Opere* (Rome: Istituto Nazionale della Nutrizione, 1968).

Grmek 1952: Mirko Drazen Grmek, *Santorio Santorio. Njegovi aparati i instrumenti* (Zagreb: Institut Za Medicinska Istrazivanja Jugoslavenske Adamije, 1952).

Grmek 1990: Mirko Drazen Grmek, *La Première Révolution Biologique. Réflexions sur la Physiologie et la Médicine du XVIIe siecle* (Paris: Payot, 1990).

Kepler 1618: Johannes Kepler, *Epitomes Astronomiae Copernicanae* (Linz, 1618).

Renn 2001: Jürgen Renn, *Galileo in Context* (Cambridge: Cambrdige University Press, 2001).

Santorio 1603: Santorio Santori, *Methodi Vitandorum Errorum Omnium qui in Arte Medica Contingunt Libri XV* (Venice: Francesco Bariletto, 1603).

Santorio 1625: Santorio Santori, *Commentaria In Primam Fen Primi Libri Canonis Avicennae* (Venice: Giacomo Sarcina 1625).

Santorio 1660: Santorio Santori, *Opera Omnia Quattuor Tomis Distincta* (Venice: Francesco Brogiolo, 1660).

Weir-Mitchell 1892: Silas Weir-Mitchell, *The Early History of Experimental Precision in Medicine* (New Haven: Tuttle, Morehouse and Taylor Printers, 1892).

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very slightly larger than the drill sizes if measured accurately.

No	inch	mm
74	0.0225	0.57
72	0.025	0.64
70	0.028	0.71
68	0.031	0.79
66	0.033	0.84
64	0.036	0.91
62	0.038	0.97
60	0.040	1.02
58	0.042	1.07
56	0.0465	1.18
54	0.055	1.40
52	0.0635	1.61

I have a few queries however which Kaare Hendrum might care to answer:

1. Is the blade a round spike or is it a flat lancet shape?

2. Does the top end of the punch give any indication whether it has been depressed by hand or does it look as if it has been struck with a hammer?

If my guess is right then the plate would have been aligned with the hole, of the drill size to be used, aligned over the point to be drilled. The two small end holes could then have been used to pin it in position. The punch could have been placed carefully over the hole in the plate and activating it would have pulled it directly into the centre of the plate hole and punched the workpiece below. The drill would then have been simply run through the plate into the workpiece with the punched mark stopping the drill from wandering.

Incidentally a company of toolmakers called Tyzack had an 'Elephant' brand of tools.'

Object 7

Member Ronald K. Smeltzer, a long-time book collector about historic scientific instruments and other scientific topics, recently acquired the lithographic printing stone illustrated in Fig. 4. Not exactly rectangular, the dimensions are about 32.5 x 23.5 x 2 cm. The text at the top reads from left to right as the stone would print:

'Mathematik. Unterabth. Geometrie, Instrumente
Naturwissenschaft
Nr. 14'

The stone has seventeen numbered drawings of instruments. At first thought, one might assume the drawings are simply generic representations of eighteenth-century instruments. However, the equatorial telescope, Fig. 5, in the lower right corner of the stone caught my attention as a depiction of Ramsden's equatorial, as illustrated on the folding plate, Fig. 6, from his pamphlet 'Description of a new Universal Equatoreal (sic), made by Ramsden, with the method of adjusting it for observation,' dated May 1774. With that discovery, I looked closer at some of the other instruments on the stone. The large theodolite in the lower left corner of the stone matches the instrument on p. 149 in J.A. Bennett's *The Divided Circle* (Oxford, 1987), taken from a plate in *George Adams's Geometrical and Graphical Essays* (London, 1791). Perhaps other drawings on the stone can be matched so closely as these two. Based upon the dating of the instruments, it seems likely that the stone was used to illustrate an early nineteenth-century encyclopaedic work, which remains to be identified. Can you identify the work?

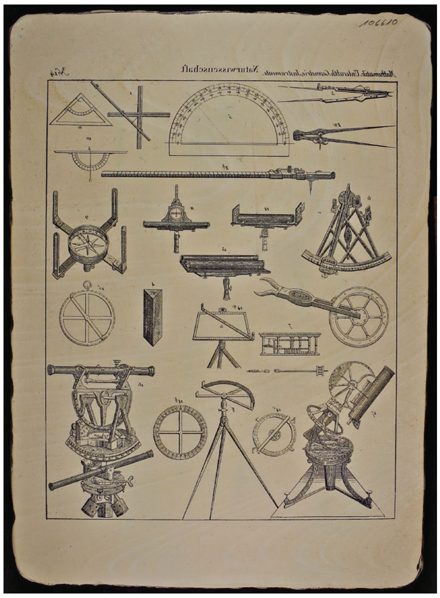

Fig. 4 *The mystery lithographic stone*

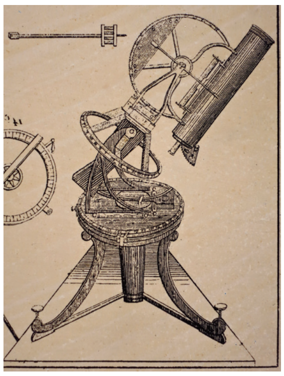

Fig. 5 *The stone's depiction of Ramsden's equatorial telescope.*

Fig. 6 *The stone's depiction of the same instrument.*