THE PULSILOGIUM OF SANTORIO

NEW LIGHT ON TECHNOLOGY AND MEASUREMENT IN EARLY MODERN MEDICINE

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Abstract. The emergence of modern science in the sixteenth and seventeenth centuries had in medicine an important field of development thanks especially to the work of Santorio Santori (1561-1636). Mostly known for his contribution to the study of metabolism, Santorio was a pioneer in the use of quantification and developed several types of instruments, among which was a device called *pulsilogium* that represents the first instrument of precision in the history of medicine. First mentioned in 1602 by a colleague of Santorio in Padua, the instrument possibly constituted a source of inspiration for Galileo and sparked an entire path of experiments in seventeenth-century Europe. Santorio presented his inventions in a series of rough engravings in his *Commentaria in primam Fen primi libri Canonis Avicennae* (Venice 1625) promising soon to publish another book called *De instrumentis medicis*: a task that, unfortunately, he was never able to fulfil. As a consequence, many descriptions related to Santorio's instruments are partial or too general to provide a proper understanding of their mechanism. In order to understand the exact application of Santorio's ideas to physiology, their reconstruction represents an essential task for any historian and philosopher of science. Relying on a new assessment of Santorio's works, newly discovered documentary proofs as well as on experimentation carried out at the University of Exeter, we present here for the first time the key principles that led to the historically accurate reconstruction of the *pulsilogium* A2. The results are possibly of some importance in the history of science, as, unlike all previous scholars, we can now prove that the *pulsilogium* represented a moment of transition and departure from the late Aristotelian physics towards Galileo's mechanics and that, despite the latter's discoveries, it

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continued to be used not to obtain an absolute measurement of the pulse rate, but to record its 'latitude'.

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Experiments with, referring to or employing the pendulum have a long history before Santorio, being witnessed in the works of Nicole Oresme (1320-1382), Giovanni Marliani (end of XV century), Leonardo da Vinci (1452-1519), and Gerolamo Cardano (1501-1576) [1]. After Santorio, the pendulum was used primarily in physics and astronomy, once it was able to provide a precise measurement of time elapsed during astronomical observations, but this would be the case only after 1602, when Galileo started pursuing his studies on isochronism in earnest[2]. Before and around this period astronomers relied on different methods of measuring time. For instance, whilst in the frontispiece of his *Astronomiae instauratae mechanica* (Nuremberg 1602) Tycho Brahe (1546-1601) sets out his endeavours by measuring and recording the values provided by three different types of wall clock, Johannes Kepler (1571-1630) still preferred the pulse's record, and tried to assess the number of pulse strokes per minute by using those of a healthy man at rest[3]. By knowing that the pulse corresponded to an average of 70 beats per minute, the count could provide a relatively reliable indication of the time elapsed in any given observation. Timing by this method however, was only ever an approximation, since it relied on inaccurate clocks and failed to take into account the real fluctuations of the pulse frequency occurring within the same hour due to factors such as temperature or slight changes in psychological attitude of the subject as well as other environmental factors. It is also worth noting that Kepler's calculation was not intended to provide a quantification of the pulse *per se*. The procedure to gain an exact knowledge of the pulse frequency consisted, if anything, in the exact opposite of what he did, and required the invention of a flexible device capable of matching the pulse rate and showing its variation through time. Thus, the solution to this problem came from the field of medicine, and was due to the work of an Italian physician, Santorio Santori (1561-1636)[4].

Santorio invented five different types of device to assess the frequency of the pulse which he called *pulsilogia*: four of which relied on properties of the pendulum. In the next section we will attempt to reconstruct the historical background of such instruments showing that, although Galileo has often been regarded as their inventor, in fact the merit should go to Santorio.

1. Historical and Theoretical Background

Given its implications for early modern science, the first requirement in dealing with the *pulsilogium* is clarification of the historical background and establishing paternity of the instrument. Unfortunately the task is not an easy one for, besides Santorio, there are at least two other potential candidates for its invention: Paolo Sarpi (1552-1623) and Galileo Galilei (1564-1642).

1.1 Sarpi, Santorio and Galileo on the Invention of the Pulsilogium

Attribution to Sarpi is entirely based on what Fulgenzio Micanzio (1570-1654) affirms in his biography *Vita del padre Paolo* (1646), in which he contends that not only two types of *pulsilogia* (corresponding to A-B in our designation), but also the thermometer and the telescope were invented by the Venetian friar[5]. With the exception of only a few notes from his collection of thoughts (*Pensieri*, no.547) Sarpi's scientific studies on the pendulum have not been preserved and the surviving testimonies do not permit us to judge with any historical accuracy what Sarpi's contributions to the evolution of this instrument were. The brief notes he wrote in the *Pensieri*, however, show that he had a particular interest in dynamics and that the topic was certainly among those he discussed with Santorio, the latter being his oldest and closest friend in Venice[6].

In the case of Galileo, historians are mostly reliant on what Vincenzo Viviani (1622-1703), Galileo's last and most faithful disciple, wrote in his biography *Racconto istorico della vita di Galileo* (1654). Viviani writes that in about 1582-3 Galileo invented an instrument to measure the pulse when he was still a student of medicine in Pisa, and he afterwards described his invention to doctors[7]. As we shall see later, this claim has no historical basis, reflecting Viviani's notorious lack of historical accuracy. Unlike Sarpi, however, attribution to Galileo can be supported with other evidence, in particular with a letter sent to Guidobaldo Del Monte (1545-1607) on 29 November 1602, in which Galileo describes some aspects of pendulum motion. Although the letter itself is not original, but is a second hand copy from another copy of Galileo's original, there is no reason to doubt either its authenticity or its date. This letter has been studied by many historians with different purposes; our aim here is not to go through all its possible interpretations but to show that, whilst the letter clearly deals with some kind of experimentation with the pendulum, it does not imply any practical application, nor does it furnish any mathematical proof for the pendulum motion. Galileo simply refers to some experiments he performed (*esperienze*) and to a plausible mechanical explanation (*senza trasgredire i termini della meccanica*), though the mathematical law had not yet been found (*è quello che cerco*)[8]. And yet, there is more. Galileo refers to the harmonious movement of the pendulum as something already known, not as a discovery he made, rather adopting it as an ideal case (in which no friction but that of the air should occur) for his theory of motion of falling bodies on an inclined plane. Moreover, experiments that Galileo is said to have performed with two persons observing pendulums of the same length with equal weights swinging with different amplitudes up to 100 times and keeping their isochronism, do not stem from any actual experience: if actually performed, the results of these experiments would have rather contradicted such an assumption: at this stage Galileo's theory was notoriously wrong as pendulums are indeed affected by the amplitude of their swing[9]. As already noted, Galileo himself makes no claims regarding inventions or practical applications resulting from his work on the pendulum. If he had actually developed any such inventions or applications he had no reason to hide them from a friend such as Guidobaldo, for describing them would have reinforced his point.

Misled by Viviani's account but also by the fact that Galileo was later able to identify the geometrical proportions upon which the pendulum swings are based, many historians have mistakenly assumed that the *pulsilogium* was invented by Galileo and was able to furnish a direct reading of the pulse rate in term of beats per minute[10]. In the following paragraphs we will show that both hypotheses are groundless.

1.2 New Documents on Santorio and the Discovery of the Pulsilogium

The first contemporary and reliable testimony referring to an instrument called *pulsilogium* appears as a quotation in a treatise on the pulse, *De pulsibus libri duo* (Padua, 1602)[11]. The author was a physician, Eustachio Rudio from Belluno (1548-1612), who was a friend and colleague of Santorio at the College of Physicians in Venice as well as professor of practical medicine in Padua, the university where Galileo taught mathematics. As we shall see shortly, the fact that the testimony does not occur originally in a work of Santorio is particularly relevant, for it testifies to the spread of application of this instrument in a wider context. In his book, Rudio acknowledges Santorio's invention in words that closely follow Santorio's description one year later:

> I just want you to know that in our age (*nostra aetate*) an instrument – which it is possible to call a *pulsilogium* – has been invented in order to discern the quickness and slowness of the pulse. Its author is Santorio Santori, a physician, a philosopher and a man provided with all kinds of erudition. This is a clearly wonderful event, and it represents a certain proof of the perspicacity and the keenness of wit of such a man. Thanks to this device, in fact, we can measure with exactness the movement and the rest of the pulse, and so the fastness and slowness of the present pulse can be compared with the one of previous days with absolute precision.[12]

Although the exact month of the publication cannot be established – for the printing licences of that period have not been preserved – there is no doubt that Rudio's book was published well before the end of 1602, since there is another edition of this work published the same year in Frankfurt by Johann Spies (1540-1623) after the first Paduan edition.[13] Spies' edition bears the subtitle *auctior* and so it must have reached Frankfurt well before the end of 1602, a hypothesis further corroborated by the fact that Rudio relates that the instrument has already been invented and applied. As a result, we can conclude that, when Galileo writes to Guidobaldo, the *pulsilogium* was already known to Galileo's colleagues in Padua. There is also the possibility that, since Galileo's interest in studying the pendulum did not seriously begin prior to 1602, his interest was reawakened by Santorio's discovery and Rudio's announcement of it, a hypothesis that is further strengthened by the fact that Galileo took part as a subject in Santorio's metabolic experiments[14]. This does not imply that Galileo relied on Santorio's studies for his discoveries, it only testifies that the first historic record of an instrument using a pendulum acknowledges Santorio as its inventor, and that – as we will show in the following paragraphs – he was working, along with Galileo and Sarpi, on a legacy of shared ideas. Finally it is particularly noteworthy that no record has been found to support Viviani's claim and all early historical quotations acknowledge Santorio's as the inventor of the *pulsilogium*.

After Rudio's announcement (1602) and Santorio's first description (1603) many other physicians and scientists started being attracted to the possibilities opened by the *pulsilogium*. Some of these records are particularly interesting.

In 1611 Caspar Bartholin the Elder (1585-1629) published a small book collecting a series of opinions on medical and philosophical problems from across Europe. One of those is a report from the Venetian physician Antonio Fabri, who confirms Santorio's invention of the *pulsilogium* and had the opportunity to witness its application to medical practice[15]. Ten years later (1621), Peter Lauremberg (1589-1635) a physician at the University of Rostok in Germany, was able to replicate and to successfully apply the *pulsilogium* to explore the usually imperceptible differences in the pulse rate (*omnigena pulsuum discrimina*)[16]. Lauremberg's quotation is relevant also for another reason: since Santorio did not provide the design of his instrument until 1625, Lauremberg could not have copied its design from any printed editions. He says he was informed that Santorio was the inventor of such an instrument (*qualia a Sanctorio excogitata accepimus*) but he had to rely on either oral accounts or manuscript sheets of the instrument, a statement that supports Santorio's later claim that his instruments were known and copied by his students and correspondents across Europe[17]. By the same token, Isaac Beeckman (1588-1637) paid particular attention to Santorio's devices and took inspiration from them for his experiments on vibrating chords.[18]

With the exception of Beeckman, these quotations do not reveal much about the mathematical or scientific background of Santorio's inventions: quite the contrary, many of them testify to his reluctance to share the secrets of his mathematical devices[19]. Unlike Galileo, we do not possess any of Santorio's manuscripts that could reveal his studies. It is quite certain, however, that he had a good understanding of mechanics, due not only to his father's military employment as *bombardiere* in Capodistria but also to the fact that he studied mathematics and music in his youth[20]. Moreover, devices such as the anemometer and the water current meter that Santorio invented and personally suggested for use in naval equipment, offer a good testimony to this.

Although Rudio's quotation does not specify when exactly the instrument was invented we can assume its date to be approximately 1590-1600. Relying on what Rudio says in the *De naturali atque morbosa cordis constitutione* (Venice 1600) about Santorio's forthcoming works, in fact, we can assume that Santorio's *Methodi vitandorum errorum omnium qui in arte medica contingunt libri XV* (Venice 1603) containing the short entry on the *pulsilogium* was already part of it[21]. There are, however, other clues that suggest we should consider 1600 as the latest possible date of such an invention, for instance the fact that, in 1603, Santorio shows that he had performed many experiments with his instrument, being already able to distinguish between 133 differences (*differentiae*) in the frequency of the pulse.

Regrettably, the hypothesis of Santorio's dependence on Galileo's studies led scholars to completely neglect the direct reading of Santorio's works, which reveal a different approach to the use of the pendulum that fits perfectly within Santorio's programme for quantification in physiology. Indeed, the description of the *pulsilogium* in the fifth book of the *Methodus vitandorum,* a work mostly devoted to differential diagnosis, stresses the need to draw exact and certain indications in medicine. Furthermore, in the various types that we will be discussing in Section II, the *pulsilogium* represents the embodiment of Santorio's 'programme of quantification' as a three-point method of empirical analysis:

a) Measurement of a physiological process through definite parameters (*perspiratio insensibilis*→change in weight; *fever*→degrees of heat; *pulse*→frequency);

b) Designing and manufacturing devices to use in order to guarantee certainty in measurement (*statera medica*, *thermometers*, *pulsilogia, hygrometers*, *wind and water current meters*);

c) An essential part of repeated and controlled experimentation.

1.3 The Physics Behind the Pulsilogium

In Santorio's earliest description (1603), the *pulsilogium* is 'an instrument able to show all the differences in equal movements' [Appendix A, Quotation I]. This statement, which will be explained in section II, highlights the most fundamental property of the *pulsilogium*, which consists in producing and recording equal intervals of time. In 1612 Santorio would reveal that the instrument was pendulum regulated [Appendix A, Quotation II] whereas in 1625 he would provide not only a drawing [Fig. 11] but also a short account of why it was capable of such regular movements. This account takes the form of a 'caveat' (*at notandum*) and, though it is not meant to provide any mathematical details, it reveals some clues about Santorio's understanding of mechanics:

> It is quite noteworthy that by pushing the ball a little more or less hard, it does not change its frequency nor its velocity, as when the space reduces, the force decreases correspondingly (*tantum amittitur de spacio quantum enim remittitur de violentia*) [Appendix A, Quotation III].

This short sentence highlights that, covering different distances in the same time, distance and velocity must be in direct proportion. In his *Storia del Metodo Sperimentale in Italia*, Raffaello Caverni (1837-1900) claimed that in this passage Santorio assumed the absolute isochronism of the pendulum, yet, in the absence of Santorio's manuscript, it is difficult to understand exactly how the Venetian physician could have reached such a conclusion[22]. Some hints come from the lexicon he adopts, which seems to be framed within the late medieval theory of 'latitude of forms' given to the use of expressions like *violentiam <intendere vel> remittere*, with which we will be dealing in the following paragraphs. If so however, Santorio's explanation most certainly draws from an understanding of the Renaissance controversy on equilibrium, which updated and successfully transformed most of the medieval assumptions on dynamics.

As Jürgen Renn and Peter Damerow have shown in a pivotal contribution on the topic, the equilibrium controversy revolved around the behaviour of weights that are deflected from their position of equilibrium over the equal arms of a balance[23]. The "equilibrium controversy" had important consequences in the development of early modern mechanics. A particularly important one, in our case, was acknowledged by the Venetian mathematician Giambattista Benedetti (1530-1590) in 1585 and stood in open contradiction to some principles of Aristotle's physics[24]: relying on Archimedes' *De aequi ponderantibus*, Benedetti asserted that the weight, and so the momentum, of a body over a balance increases in proportion to the distance from the fulcrum[25] [Fig. 1]. As a result, if one of the two weights is lifted and the other is allowed to move freely downwards, it will arrive at the point of rest (viz. the centre of gravity) more rapidly if falling from a more distant position over the horizon and, vice versa, less rapidly if falling from a closer position, regardless its original weight[26]. In short, it will acquire greater or lesser momentum (*intendit aut remittit violentiam*) according to the distance traversed so that, to smaller distances traversed would correspond less force and vice versa, exactly as in Santorio's description[27]. To understand this point we have to bear in mind that within the Aristotelian framework, the momentum of a body (*violentia*) was still related to its weight, which in this case changes depending upon its position.

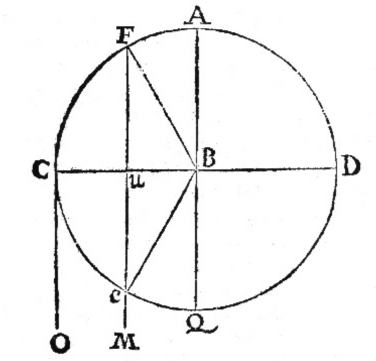

Figure 1. Benedetti's demonstration that the weight of body depends upon the distance from fulcrum. The direction of the weight is expressed by the perpendicular, so that it progressively decreases the more the weight CO comes closer to the centre of gravity laying on the line QBA as it is in the case of the perpendicular FM.

The idea that weights had a different efficacy according to their position over the arms of the scale, was already known in Arabic science as the problem of *gravitas secundum situm* ('positional heaviness'). This concept was particularly important in the case of scales with unequal arms (*staterae*), where a smaller weight on the longest arm could counterbalance a greater one on the shortest [Fig. 2]. Being a case of equilibrium and an application of the principles of the scale, movement was chiefly conceived as obeying a circular motion. As Jurgen Renn and Peter Damerow put it: "[t]he proximity of the descent of a weight moving in constrained motion, on the one hand, and the natural motion of a weight to the centre of the world, on the other, is determined by the angle of contact between the circular path of constrained descent and the straight line of direct descent to the centre of the world."[28].

Figure 2. Apianus' edition of Iordanus Nemorarium *Liber de ponderibus* (1533). Engraving from the frontispiece, showing the mechanism of the steelyard according to the Aristotelian principles of mechanics

Equally relevant were the outcomes that philosophers and engineers were able to draw from this debate in the early modern period. Del Monte, for instance, applied these principles to a particular case in which the centre of the world lies at the bottom of the circle described by the balance, a problem that seems to lie at the very foundation of Santorio's and Galileo's approach to the pendulum [Fig. 3][29].

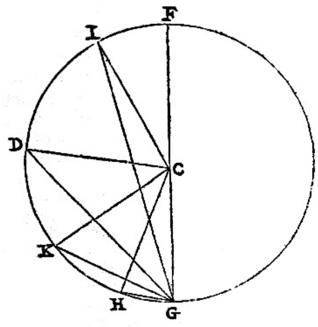

Figure 3. Del Monte's example of a balance whose centre of gravity lies at the bottom of the circle.

The indications that Santorio came to his conclusion from the development of this debate are many: the fact that he studied mathematics in Venice, where Benedetti's legacy was well alive, and that he graduated in Padua, where Guidobaldo Del Monte (1545-1607) had studied; Santorio's familiarity with statics in his long running experiments on metabolism as well as his reading of the works of Heron of Alexandria, which give considerable attention to the problem of equilibrium of weights [30]. Furthermore, we found a confirmation of this theoretical proximity between Del Monte's development and Santorio's approach in some copies of the little-known second edition of the latter's *Commentaria in primam Fen primi libri Canonis Avicennae* (Venice 1626) displaying some additional notes on instruments, not reported or displayed elsewhere. In one of these, Santorio states that all the *pulsilogia* keep constant proportions between their swings as their frequency increases or decreases according to the larger or smaller arcs of circumferences described by the pendulum (*rotae portio*) [see Appendix A, Quotations IIIb] [31].

In short, then, the question of the pendulum's motion stems from the equilibrium of weights and if one considers that Santorio's most famous invention was a platform scale (*statera medica*) designed to measure the metabolic dynamic, and that many of the instruments he invented imply complete familiarity with static principles (as the already mentioned anemometers and water current meters), the transition from one to another does not seem particularly surprising, nor does it require any reliance on Galileo's studies [Figs. 4-6].

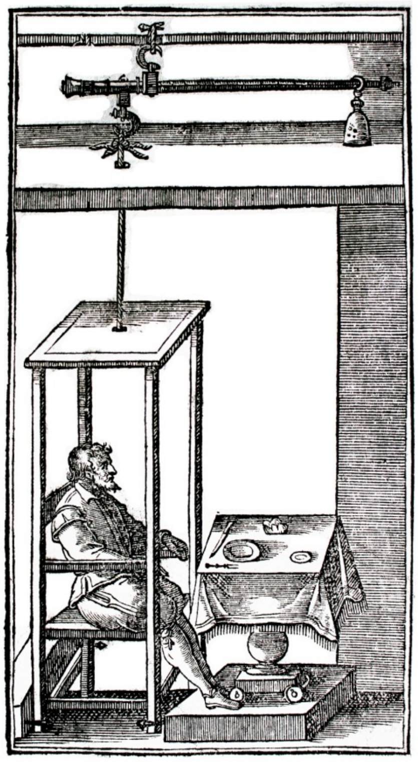

Figure 4. 'Statera medica'

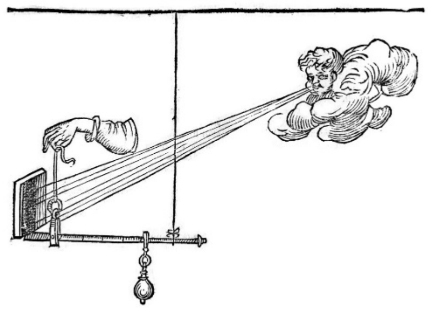

Figure 5. Anemometer

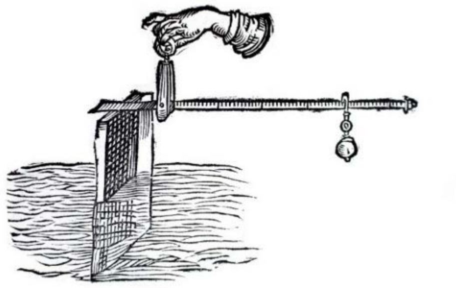

Figure 6. Water current meter

All the examples presented hitherto however, could lead to a reasonable explanation of the pendulum only if applied to a specific case: the vibration of cords. When a cord vibrates, in fact, the pitch remains constant even though the vibration – namely the space traversed between two consequent oscillations – is greater at the beginning than at the end. This is an empirical fact, not requiring the assumption of any theory, and, as seen, it could have been known to Santorio given his musical background. The idea of applying the positional heaviness and equilibrium to the study of vibrating cords must have been quite common in the early modern period, for we find this exact procedure in Isaac Beeckman (1588-1637).

On the 1st December 1630 Beekman notes in his *Journal* that reading Santorio's *Commentary on Avicenna* gave occasion to him to investigate the reason why cords of tortoise vibrate by passing different spaces in the same period, given the fact that the vibration is greater at the beginning than at the end[32]. The solution he finds reveals how the theory implied by Santorio's instruments was understood in the immediate aftermath of their discovery:

> Let then *ae* be the rope from which the weight hangs perpendicularly. Let rise the same weight up to *b*; it is clear that, in this position, it has as much force to fall down as if it would not have been bound to the rope. Let divide *be* into two equal parts, so that the angle *bac* will be the half of the right angle *bae*. As a result, the force *fb*, *gc* which pulls downwards or that from up pushes downwards, is double more in *b* than it is in *c*, as it exercises its pressure only on the angle *ach*, which is the half of *abf*. Indeed, the particles that press the weight *c* (that whilst the weight *c* is at mid-way tend downwards according to the vertical line) affect that weight only for half of their virtue [Fig. 7][33].

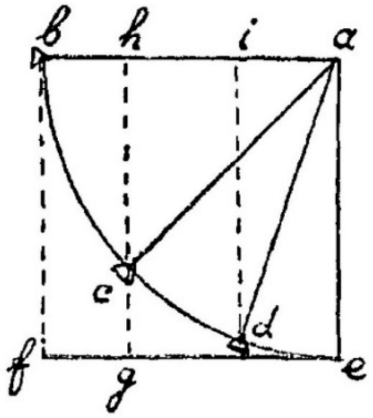

Figure 7. Beeckman's diagram explaining the isochronism of vibrating chords (1630).

In the margin, Beekman notes that such a condition is only ideal, as experimenting with the same phenomenon in air with mass of different weights would produce different results according to the weights applied. As it clearly appears, then, the principle of positional heaviness is pivotal in understanding Santorio's use of the pendulum in medicine, and from this standpoint it is equally important to note that many of Santorio's followers substituted the name *pulsilogium* with one reflecting the principle from which it stems, calling it *libra sphygmica* ('sphygmic balance')[34], a transition which in the history of technology would become even more apparent later on, in the case of pendulum scales, whereby the vertical thrust of a weight on a dish is counterbalanced by the inclination of a lever over a graduated scale [Fig. 8].

Figure 8. An example of 'Pendulum Scale'

1.4 What does the Pulsilogium Measure?

Whatever the theoretical explanation behind the *pulsilogium* might have been, his understanding of the properties of the pendulum allowed Santorio to accurately collect, record and compare various data resulting from his measurement of the pulse. The physician had only to synchronise the swing of the pendulum with the frequency of the pulse and subsequently take note of the result. But what kind of measurement did use of the *pulsilogium* allow?

According to the statements we carefully collected from his various works and which are reproduced at Appendix A, the *pulsilogium* is intended 'to measure the degree of distance' (*gradus recessus dimetiri*) between healthy and unhealthy disposition in the body. Once measured, this distance becomes a proper quantity (*quantitas recessus*), and this possibly explains why Santorio uses the terms *degree* and *quantity* interchangeably. The range of this distance – that we might better refer to today as 'variability' – is called by Santorio and by the Renaissance physicians *latitudo,* or 'range', a term that could be applied to the neutral, healthy or diseased state of the body (*latitudo neutralitatis, sanitatis*, *morbi*). According to Santorio, in fact, the 'latitude of health' embraces also the 'latitude of disease' (*latitudo morbi*) as the last degree of its own range[35]. The terminology adopted reveals that, once again, the Venetian physician is basing his conclusions on a particular development of the scholastic theory of the 'latitude of forms' (*latitudo formarum*).

Developed in the fourteenth century, especially in the works of English philosophers of the so-called *Merton School*, this theory had already had an important precedent in the field of medicine where – at least from Galen onwards – the concept of degree played a pivotal role in understanding the action of drugs and temperaments on the body. It was however only in the medieval period that the concepts of degree and latitude overlapped and gave origin to a sophisticated theory of physical transformation in matter. According to the *latitude of forms*, in fact, qualities such as heat, light and movement must be regarded as properties of a determinate substance that undergo a series of continuous changes. For this reason the theory was also known as *intensio et remissio formarum*, that is to say the capacity of forms to stretch and contract differently in corporeal substances. Being continuous as well as referred to a particular quality, these changes supposed a *minimum* and *maximum* in the range of their variability (*non gradus/gradus summus*), and could be expressed theoretically by means of an incremental scale of degrees, usually comprehended between 0 and 8[36].

The transition from the concept of latitude to the use of quantitative parameters by means of instruments devised for this purpose represents one of the greatest breakthroughs in the history of science and, in medicine, the merit for this transition should be ascribed to Santorio. Most notably Santorio succeeded in adopting and systematically applying the notion of 'magnitude' (*magnitudo*) to the Galenic concept of equilibrium by converting the rapports of proportion/disproportion of bodily temperaments into linear segments of variable length (*recessus*) departing from or approaching to a mid-point representing the equilibrium[37]. In this way he could then treat disease and healthiness as different regions over a scale of degrees, all of them accountable. Such an approach marked a radical departure from the practice of subjective appreciation of temperaments and bodily disposition which was dominant in any aspect of medical practice still in the seventeenth century. Before Santorio, degrees were used as theoretical entities, meant to classify the various aspect of a phenomenon and the idea of associating each degree with a real number was open to serious obstacles, related to the impossibility of setting determinate fixed limits on the range of variability of the phenomenon. This was even more the case in medicine, in which not only was the possibility of setting such limits openly rejected by Hippocrates and Galen, but its actual application was (and to some extent still is today) hindered by the peculiar constitution of each patient (*idiosyncrasy*). From this standpoint, it is particularly remarkable – but after all not surprising – that the transition from degree to quantity occurred chiefly in the field of medicine.

According to our study, however, this transition is still ongoing in the case of the *pulsilogium*. In Santorio's account [Appendix A, Quotation I], in fact, the distance between the *maximum* and *minimum* range of the pulse frequency should be expressed as a linear scale between two points which he explicitly relates to the rarest and fastest pulse observable in normal conditions[38]. Since we know that the measure of pulse rate increases geometrically but the measurement expressed by the *pulsilogium* is linear, the instrument was unable to provide a direct reading of pulse rate: this was not in fact its intended purpose.

1.5 Uses and Applications of the Pulsilogium

The *pulsilogium* was meant to be used as a comparator. Its purpose was to reveal small variations of frequency allowing the physician to sketch out a reliable framework of the health trends in his patients [Appendix A, Quotation I-II]. The reasons why such variations were indeed considered to be 'small' were both practical and theoretical. As for the practical ones, Santorio repeatedly highlights the fact that any major increases or decreases in the pulse frequency are quite noticeable (*sensibiles*) and do not require the use of any particular instrument for them to be detected – although issues clearly arise as to how the objective value pinpointed at any time by such variations is determined. Theoretical reasons, are instead directly rooted in Santorio's understanding of physiology as the process by means of which the body maintains (*conservat*) its normal functions by insensibly (*insensibiliter*) approaching or receding from the point of equilibrium; a process that in the *pulsilogium* is translated in the act of adding or subtracting degrees from a given number[39]. More precisely, the device allows a comparative measurement of the pulse expressed as a difference between two or more consecutive measurements.

If the pulse which in one hour/day is found to be 70 degrees, is in the following one found to be 65, Santorio would record that it has decreased by 5 degrees. In this way, each successive measurement yields the difference between pairs of measurements. This means that Santorio's measurements were basically collected and recorded in terms of ratios (*proportiones*): since the pulse frequency tends to remain constant in normal conditions that would give the same indication on the instrument scale. In other words, two consecutive measurements with the same result would have been marked as ratio 1:1 whilst regular increase or decrease of frequency could be reported as ratios of 1:2, 1:3, depending on the result found. On the other hand, irregular increases or decreases of the pulse frequency would have been recorded as simple comparison of degrees (60:55; 60:45, etc.). Santorio in fact specifies [Appendix A, Quotation I] that by means of the instrument it is possible 'to observe all the ratios pertaining to the pulse' (*omnes proportiones observare*) and we know from other accounts that the term 'ratio' (*proportio*) was sometime used quite literally, as Santorio used to collect results from its statical experiments just in terms of mathematical proportions[40]. It is worth noting that, from a practical point of view and for the sake of medical diagnosis alone, the exact notion of the number expressed by each degree (in terms of beats per minute) is not necessary: it is enough to record the degree and monitor the trend of health in each patient.

Despite the fact that Santorio was not very keen on providing details on how he recorded his results, this conclusion follows directly from what he states in 1625 [Appendix A, Quotation III] and is further corroborated by the kind of practice that was adopted with the spreading of the instrument as a diagnostic tool by Marek Marci (1639) and Athanasius Kircher (1665) [Fig. 9-10], the latter in particular providing a very clear explanation of the kind of measurement permitted by instruments that are akin to or derived from the *pulsilogium*[41].

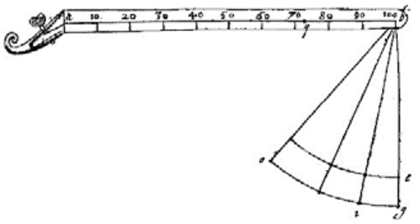

Figure 9. Marci's 'Pulsilogium' (1639)

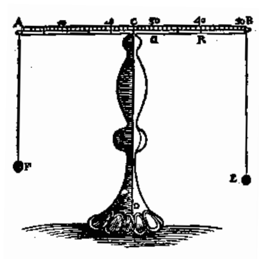

Figure 10. Kircher's *Filochronometro* (1665). Rather than being provided with a tapered/tuning peg on one side, as in Santorio's and Marci's design, Kircher's instrument presents two weights that can be pulled up and down in order to match the increase or decrease of pulse frequency.

When used in medical diagnosis, the *pulsilogium* required a pre-assessment of the general condition of the patient so that changes in frequency could be associated for instance with morbid conditions (especially fevers). As already noted, whereas great variations are easily perceived by any doctor, the smallest ones can be such that even a well-trained physician can fail to perceive them, thus leading to errors in diagnosis. In this sense, the invention of the *pulsilogium* serves to provide an objective appreciation of the values linked to any such variations. The point is clearly underlined by Józeph Struš (1510-1569), author of what was arguably the most influential sixteenth-century book on the pulse:

> In truth, there are more than fifteen simple pulses we already accounted for, but some of them are useless to a physician; others instead are useful but are impossible to be recognized at the human touch. [...]. Those that are useful but cannot be detected by the touch (*imperceptibiles*) may nonetheless be converted to those already discussed and they are the *pulsus longus*, *latus*, *altus* and those opposed to these, that are the <*pulsus*> *brevis*, *angustus* and *humilis* [...].[42]

The fact that the *pulsus humilis* is highlighted by Struš as 'useful for the diagnosis but imperceptible' can be profitably put in relation with the kind of analysis Santorio pursues in his investigations. Useful but imperceptible means that its existence can be logically deduced by the mathematical combination of all the other species of the pulse, but cannot be detected by the senses. This is indeed one of the most important concerns Santorio's instrument is meant to address, as the *pulsilogium* aims at extending the doctor's senses far beyond their natural limits in order to perceive what would otherwise remain obscure and unknown[43]:

> [...] by means of the pulsilogium we distinguish between the *pulsus humilis* and the *pulsus invalidus* in the following way: if the pulse that has previously been strong *(durus)* and frequent reduces its strength and frequency then it will be a *pulsus humilis*, most of the time, in fact, the *pulsus humilis* does not decrease its frequency: when very slight the difference between the increase and decrease in frequency *cannot be recognized by a physician without using the pulsilogium* [Appendix A, Quotation VIIIb, see also Quotations IIIa and IIIb]. Our emphasis.

This passage appears to suggest application of the *pulsilogium* when pre-assessing the patient's condition and determining how the pulse fits within the Galenic classification (*magnus*, *durus*, *mollis*, *humilis,* etc.). As Santorio recognises, in fact, frequency *per se* is an equivocal parameter, inasmuch the 'latitude of health' might encompass different frequencies[44]. As such, this classification provides the framework within which Santorio puts his instrument: having carried out a preliminary assessment of the general and invariant qualitative aspects of the pulse, the physician had only to measure the degree of frequency for each of them in terms of *aequalitas* or *inaequalitas*. Others factors remaining the same, 'equal pulses' (*pulsus aequales*) resulted in having the same degree/frequency over the *pulsilogium*, whereas 'unequal pulses' (*pulsus inaequales*) resulted in showing different degrees/frequencies over time. In the latter case, each species of the pulse was susceptible of a range of variability (*latitudo*) specified as a particular region of the overall range of the *pulsilogium* scale marked as a difference between two or more degrees, and so as a numerical ratio (*proportio*). As we will show in Section II, the correct understanding of this point was essential to addressing the question of what Santorio's 133 differences stand for.

By assigning a quantitative number to each species, Santorio possibly anticipated a method subsequently used by others, and especially adopted by John Floyer (1649-1734), though in the latter case the classification was provided in terms of beats per minute rather than degrees[45]. Such a method could be used either as an application of the Galenic classification (marking the range of variability for each species) or as a method to correct some of its assumptions in the light of the measured frequency; this explains why Santorio emphasises that one of the main advantages of his instrument is its ability to better classify and distinguish between *pulsus humilis* and *debilis*.

Such an approach is further revealing of Santorio's understanding of how to use precision instruments in diagnosis. The *pulsilogium* is not intended to replace the traditional physiology but to support it, by helping the physician to draw precise conclusions (*indicationes*) on the present condition of his patients and on the quantity of drugs and food to be supplied. Indeed Santorio clarifies that, whilst other factors are also important to evaluate the general condition of a patient, the doctor should be focusing only on those characteristics of the pulse that belong *per se* to its definition, and these are the motion and rest of the arteries. In the modern world, where every aspect of the human physiology has already been subjected to quantitative analysis, it is probably difficult to grasp how protracted and fruitless discussions on the exact nature of the pulse could be during and well before the early modern period, where a subjective interpretation of pulse frequency could result in a drastically different diagnosis, with an associated array of sometimes onerous and damaging treatments.

The need to draw a correct conclusion by means of instruments of precision would remain largely faithful to Santorio's standards until the work of John Floyer (1649-1734) and Pierre Augustin Boissier de Sauvages (1706-1767). From this standpoint is interesting to note that, although in 1695 Guillaume Amontons tried to substitute Santorio's *pulsilogium* with a clepsydra[46] and in 1707 Floyer introduced a pocket watch for the direct reading of the pulse frequency, their new methods were not easily accepted (not least because Floyer's methods were weirdly mixed with different notions of western and Chinese medicine). So much so that in 1752 Boissier De Sauvages and his students still proposed to rebuild a replica of the *pulsilogium* in order to avoid sterile discussion at the patient's bedside[47].

Due to the lack of his tabulated data, it remains unclear whether by means of the *pulsilogium* Santorio also collected data from his patients according to their temperament, age and gender. What is certain is that the method Santorio adopted allowed him to pursue the very first statistical analysis of these data ever recorded in the history of medicine. We know in fact that Santorio used his instruments to assess the conditions of those patients he had never seen before, by comparing their temperature, frequency and weight with the average obtained from previous measurements on other subjects[48], an aspect further highlighted by his constant use of the plural in referring to the subjects of his experiments (*sani / aegri homines*).

Many of the details synthetically presented in this section will be now discussed analytically in the following sections concerned with the theoretical and technical issues faced during the reconstruction of this instrument.

2. Towards a Reconstruction

In preparing for the first historically accurate reconstruction of the *pulsilogium* our first step was to distinguish between two uses that Santorio assigned to his instrument as well as between the various types he invented. As seen in the previous section, the *pulsilogium* was intended to record pulse's frequency but was also used as a reliable timekeeper; the latter use is particularly witnessed in Santorio's experiments involving the thermometer [Appendix A, Quotation VI]. For the time being though, we choose to focus on its primary use as explanation of this leads to the further application of the instrument as a timekeeper.

2.1 Classification

A general classification of all the engravings presented in the 1625 edition of the *Commentaria in primam Fen primi libri Canonis Avicennae* constituted the second step.

By grouping pictures according to similarity in external shape and design, we classified them into three main types, that are hereby marked with letters (type) and numbers (model) in order to specify their variants [TABLE 1].

CLASSIFICATION OF SANTORIO'S PULSILOGIA

A	or *Beam type*	1	The beam is divided in 80 degrees	[Fig 11]
		2	The beam is divided in 70 degrees [not marked only displayed]	[Fig. 12]
B	or *Dial type*	1	The dial is divided in 12 degrees	[Fig. 13]
		2	The dial is divided in 24 degrees	[Fig. 14]
C	or *Pocket watch type*		Featuring 7 divisions (*differentiae*) + 7 subdivisions (*minuta*)	[Fig. 15]

Table 1.

A

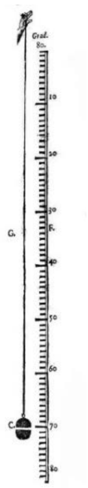

Figure 11. A1

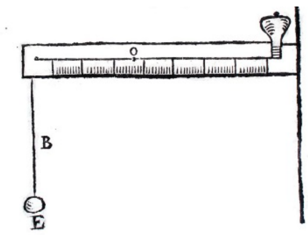

Figure 12. A2

B

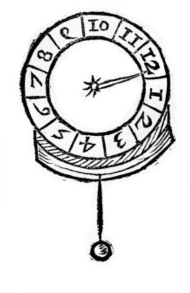

Figure 13. B1

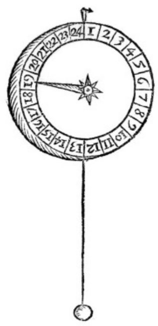

Figure 14. B2

C

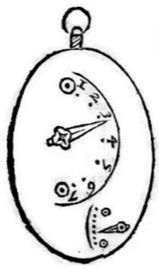

Figure 15.

Despite some improvement in design, *Pulsilogia* A1-2 have been considered as belonging to the same type insofar both adopt a graduated beam (which in A1 is possibly a ruler), used vertically in the former case and horizontally in the latter.

Serious consideration was given to the extent to which the images could be relied upon as accurate illustrations of the instruments, as this is notoriously problematic when referred to the design of seventeenth-century instruments. It was possible in fact that the artist had limited access to the instruments with no time to study them in detail or that he produced the drawings from a description, without direct access to the instrument in question. However, due to their poor quality (the rough sketches provided by Santorio were meant as preliminaries to the elaborate plates he prepared for the *De instrumentis medicis*), it is almost certain that Santorio either drew these images himself or was directly involved in their production. For the 1625 engravings represent the only available source we have for the original *pulsilogia*, we had no other choice than to trust them, though we constantly checked their information against historical documents, both visual and written, and data provided by our experiments.

2.2 Collecting References and Establishing Criteria

A third step was to collect all the available descriptions provided by Santorio himself as referring to the *pulsilogium* [Appendix A].

Insofar it was not related to any particular device, Santorio's earliest description [Appendix A, Quotation I] has been used as a standard description[49], although there is the possibility that *pulsilogia* B1-2 worked on a slightly different principle.

For all the references he makes to them, Santorio's accounts never relate the real functioning or mechanism of his devices, but only their purpose: a caution that he extended to all the other instruments in order to avoid plagiarism by his pupils. This notwithstanding, a comparative reading of these accounts is particularly useful, for it sets out the criteria for application, lists all the possible uses of the *pulsilogium*, and features some details that are noteworthy and summarized below:

Criteria

a) Measurement must be always taken in healthy men;
b) Measurement should define the minimal differences in the pulse variation, not the notable ones.

Uses

a) Measuring the motion and rest of the artery;
b) Exactly identifying the pulse frequency and enabling to repeat the control at any time;
c) Identifying regularity/irregularity of the pulse;
d) Recording and comparing data;
e) Defining the range of normal/abnormal activity in each patient.

Details

- The instrument is able to show 133 differences of the pulse frequency.

2.3 Recreating the Scale: [1] Motion and Rest

The first point listed under *Uses* deserves particular attention. Indeed, whilst the measurement of the 'pulse frequency' (*motus*) can result in something intuitive for modern scholars to grasp, the idea of 'rest' (*quies*) might possibly not, thus requiring some explanation.

In Galenic medicine, the *rest* constitutes an important therapeutic indication as it is revealing of qualitative pulse features such as its *latitudo* and *parvitas*[50]. In this case, rest (*quies externa*) refers to the *distensio* of the artery and can be described as the time interval between two consecutive strokes of the pulse. As such, when the interval decreases (*remittit*), the velocity increases (*intendit*) and vice-versa. Accounting for both these values the *pulsilogium* should provide two types of indication but Santorio shows only one in his engravings. This led us to devote more serious consideration to the position of the scale of the *pulsilogium* A1 [Fig. 11]. Here the length, still numbered in degrees (*gradus 80*), runs from 0 degrees at the top to 80 at the bottom but, if it was meant to account for the increase of frequency alone, then the scale should have been reversed. Conversely, if one takes into account Santorio's caveat about the *pulsilogium* measuring not only the *motion* but also the *rest* of the artery, the scale shown might represent the interval of time (*velocitas*) and so the 'greatness' (*magnitudo/latitudo*) of the artery's rest. This use might have been helpful especially in cases where the frequency didn't perfectly match the regular oscillation of the pendulum. In this case, in fact, whilst the degree over the beam indicated the velocity, the frequency, that is to say the number of strokes per pendulum cycle, could be accounted for mentally. Conversely, when the strokes perfectly matched the swings, the degree revealed the frequency indicated by means of the white line drawn over the little ball A1 [Fig. 11], or by the small knot/wooden bead in A2 [Fig. 12, letter O]. We also know that Santorio used the A2 as a timekeeper in experiments on the temperature of light and fever, which confirms the idea that the *pulsilogium* provided a dual indication.

A good test for our hypothesis was the comparison with the *dial pulsilogia* (B1-2) where not only the reverse scale disappears, but degrees are in direct proportion to the increased frequency. Initially we thought that, by constantly using the device, Santorio realised that frequency was a sufficient indication for measuring the pulse, and that, being just its reverse, the rest could have been counted mentally. But this later proved to be a false trail. Santorio, in fact, uses the *dial pulsilogia* to measure the respiration cycle and seems to account mentally for the number of pulse beats within it [Appendix A, Quotation VII]. Besides, removing the scale indicating the 'period of rest' meant in fact the removal of the period of time, without which frequency could not be evaluated.

2.4 Recreating the Scale: [2] A Double Indication?

To better understand this point it is worth remembering that in late-Renaissance physics 'frequency' and 'velocity' were still considered unrelated parameters. As Stillman Drake has shown, at this point in history velocity was not the ratio of time elapsed to distance traversed but was expressed purely as a number of degrees that could be added or subtracted, exactly as Santorio does.[51] If the degree related to the interval of time disappears, then the degree of frequency must result in 0, because it happens in no time. Thus, the double indication provided by the beam *pulsilogium*, (frequency/interval of time or rest), must be retained also in the B1-2 types, although possibly in a different and more subtle way.

As before, in this case a careful reading of Santorio's quotations proves enlightening.

In Appendix A, Quotation VI, Santorio states that the dial *pulsilogium* (*cotyla*) measures both *time* and *frequency*, allowing evaluation of the difference between diastolic and systolic pulse. Since, in Galenic medicine, inspiration corresponds to diastole, expiration to systole, he measured their difference by synchronising the swing of the pendulum at the lowest degree of the dial, say 1, in order to match the cycle of respiration and by subsequently increasing the degree over the dial in order to match the frequency of the pulse. In case of asynchrony, the number of pulse strokes could be accounted mentally. This represents a further proof that the kind of measurement Santorio was pursuing with the dial *pulsilogium* resulted in a comparison of degrees.

Whether or not the B1-2 had a particular mechanism that allowed the double registration of this value is not clear. Certainly these devices didn't simply consist of a single thread wound around a pivot, for illustrations of both B models show a bulky box (*cotyla*) respectively underneath (B1) and behind the dial (B2) which would have been of no use in that case. This is also proved from a careful analysis of the B1 design [Fig. 13] that features both a moving hand and moveable dial (indeed the dial is shown rotated clockwise). It is also clear that, whatever the mechanism of these *pulsilogia* might have been, the numeration over the dial (12-24 degrees) was intended to allow for improved measurement resolution.

Another important difference between the beam and the dial *pulsilogia* was the number of degrees on scale or dial. In A1, this scale is divided into 80 degrees [Fig. 11]. As already seen, in the doctrine of the 'latitude of forms' *(latitudo formarum)* 8 stands for the maximum degree of intensity (*gradus summus*), so we can assume that Santorio's intention was to divide this classic 8 degrees of intensity into tenths. This hypothesis could be corroborated not only by Santorio's general understanding of physics, as described in Section I, but also by the fact that he used to assess the scale of his instruments – the thermometer for instance – on a minimum and maximum range of variability[52]. However, in keeping with what has been said before, the degree 0 would correspond to no time (being signalled in scholastic terms as *non gradus*), so most of the scale intervals between 0 and 1 would represent time intervals too short to correspond to an actual range of the pulse in a healthy man. Thus it is possible that in the A2 Santorio completely suppressed the numbers between 0 and 1, and accounted for the real range of the pulse frequency (10-80) rather than for its ideal range (0-80), which would possibly explain why the A2 instrument has a scale of 70 divisions (that is to say 7x10) over the beam. A comparison with *dial pulsilogia* B1-2 shows in fact that the minimum degree is 1, not 0. It is noteworthy that the scale adopted was not common to all later examples of *pulsilogia*: in Marci's *pulsilogium* we find a scale of 100 degrees whilst in Kircher's the scale accounts for 50 degrees which means that it depended on the range and resolution sought by the physician at the time[53].

2.5 Recreating the Scale: [3] Understanding the Expression "Differences of [Un]Equal Movements"

But there are also other aspects of Santorio's description that deserve particular attention. In Appendix A, Quotation I, Santorio emphasises that by using the *pulsilogium* he had identified "133 differences of equal movements, starting from the slowest up to the fastest". In his account, Santorio swaps the name *aequales* and *inaequales motiones*, an aspect that left us completely puzzled initially.

The quotation reads as follows:

> [...] exhibet enim instrumentum omnes aequalium motuum differentias, quae sunt centum et triginta tres incipiendo ab osservatione rarissimi motus usque ad creberrimum [...]: totidem observantur differentiae [in]aequalium motionum. Ex cuius pulsilogii observatione primo colligimus qualibet die, et hora quantum aegri recedant in crebritate a statu naturali, secundo infallibilem notitiam praebet, qua hora desinat augmentum, incipiatque status, et declinatio: tertio observatur virtute proportionum aequalium motionum in pulsilogio observatarum, quam crebritatem, quam intermissionem, et quietem externam quolibet individuum perpeti, et non perpeti potest.[54]

Note that the term *motus* is applied here alternately to the pulse frequency and to the motion of the pendulum, insofar at least as they match each other. We thought there might have been a mistake in the printed text, as most of Santorio's quotations about instruments are inserted rhapsodically and sometimes contain easily identifiable imprecisions [for instance, Appendix A, Quotation VI]. Yet, the alternation is kept unchanged also in all the following editions of the *Methodus vitandorum* (Venice 1630, Geneva 1631-32).

We decided to proceed analytically, by looking at the meaning of *equality* and *inequality* as referring to the pulse in Santorio's and contemporary texts.

As noted in Section I, we knew that *aequalitas* referred to a pulse whose parameters are constant over time, whilst *inaequalitas* indicates a variation[55]. Since the *pulsilogium* was able to assess only the frequency (motion and rest of the artery) *inaequalitas* should refer to the parameter whose range of variation could be assessed only *caeteris paribus*, that is all other factors remaining the same. This meant, of course, using the measurement within the framework of the traditional theory of the pulse, as frequency alone could not represent a reliable parameter in diagnosis. We knew also that equal pulses resulted in the same position over the beam, whilst differences could span within the range marked by each species distinguished by the Galenic rationale. We further assumed that Santorio applied the *pulsilogium* to define the exact range of each species, especially in fevers and other conditions in which frequency can be altered. Thus, insofar as *aequalitas* and *inaequalitas* are denoted by the same device and in a reverse way, Santorio using these expressions alternately is a *Freudian slip* revealing the *pulsilogium's* capability to account for both of these values. As a result we amended the text to read *differentiae aequalium motionum*.

In the absence of further data it is impossible to understand fully how the 133 differences were distributed, but there is no compelling evidence that they had a linear distribution. These differences, would possibly result in figures annotated in a separate sheet or registered mentally by Santorio, for the number does not appear in any of the surviving drawings. Allowing that 133 is the result of 19x7 and that 7, as a number that accounts for differences in frequency, is openly acknowledged by Santorio in his reference to the *pulsilogium* D [Appendix A, Quotation IV], it is reasonable to assume that there were 7 overall genres into which the 133 were subdivided, but we don't have enough information to decide upon which species or genre they referred.

2.6 Capacity of the Pulsilogium A2

In almost all his descriptions, Santorio highlights the fact that the slowest and fastest movements should also be referred to the measurements taken in healthy men (*sani homines*). This expression refers to a qualitative pre-assessment of the patient's condition and resulted in a series of repeated experiments intended to identify the normal range of the pulse, firstly defined according to the general conditions of each individual and afterwards possibly extended to a wider sample. We found confirmation of the adoption of such a statistical approach in what Santorio says in his *Commentaria in Artem medicinalem Galeni* (Venice 1612) as well as in a letter to Galileo dated 9 February 1615 about the sample of individuals used for his statical experiments; this sample encompassed 10,000 subjects for a period of over 25 years[56]. Such an approach must have led him to assess the normal range of the pulse which, regardless of the historical capacity of the instrument, we know spans between 60-100bpm[57]. This in turn gave us an insight into the overall length of the A2 that will be explained in Section III.

2.7 The Overlapping of Linear and Geometrical Measurement

A rather serious question that arose quite early in the reconstruction process, was to evaluate whether the overlapping of linear and geometrical progression in the evaluation of the pulse could have hindered the ability to use the instrument effectively.

The answer came from a reading of Santorio's own account as well as from our experiments with the *pulsilogium*.

In Quotations III and VI Santorio explicitly states that the *pulsilogium* is meant to measure only small variations of the pulse, not the great ones (*non quaerimus notabiles differentias sed illas minimas*). By using the *pulsilogium* we noted that, when used in this way, the error resulting from the overlapping of linear and geometrical scale is for all practical purposes negligible. It should equally not be forgotten that the adoption of a linear scale does not constitute an historical proof against Santorio being aware of the so-called 'law of the wire' – that is, the pendulum period depends upon the square root of the distance from the point of suspension to centre-mass. In Marci's *De proportione motuum* (1639), in fact, a mathematical proof of this is clearly given and, nonetheless, the Bohemian physician still uses the *pulsilogium* in a way that is identical to that of Santorio.

2.8 Margin of Error

The engraving in Fig. 12 shows a vertical line on the right-hand edge of the drawing which we interpreted as evidence that the *pulsilogium* A2 was attached to a wall or a fixed vertical stand. Indeed, as highlighted by Kircher[58], the perfect immobility of the pendulum's support is an essential prerequisite for the correct functioning of the instrument. This detail led us to consider possible sources of error and the overall margin of error the instrument was subject to.

The advice given in Appendix A, Quotation I that the measurement must not only be 'quick' but also 'exact' (*pro qua cognitione cito et exacte comparanda*) shows that

Santorio realised that the margin of error involved in the *pulsilogium* use was minimal and almost entirely due to the human operator. This aspect is highlighted in a quite rare and very short article devoted to Santorio's *pulsilogium* written in 1979 by Jeffrey Levett and Gyan Agarwal, whereby the effect of error introduced by the human operator is illustrated by reference to a system diagram that we have reproduced below [TABLE 2][59].

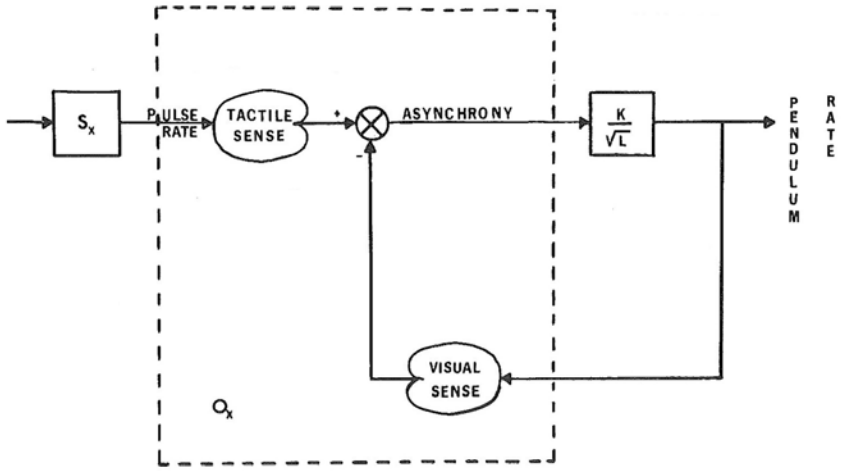

Table 2. Levett and Agarwal's System Diagram of Santorio's pulsilogium.

As illustrated here, critical to the precision of this measurement is the operator's ability to accurately synchronise pendulum motion with the patient's pulse. Operator errors here will bias the error signal which will add or subtract an offset to the value of L in the function responsible for controlling pendulum rate. The *pulsilogium* is modelled as part of a closed-loop control system employing negative feedback. The patient's pulse rate provides the set-point (Block labelled S_x at upper left). The operator (O_x) has both tactile sense of the set-point and visual sense of the pendulum rate (Feedback to visual sense at lower right). Subtracting feedback from set-point produces an error signal – here labelled as 'Asynchrony'. This error signal, whose magnitude and sense is proportional to the difference between feedback and set-point, is used to adjust the value of L in the function describing pendulum motion (Block at upper right). This in turn corrects the pendulum rate to drive the error toward zero. Assuming correct calibration, when zero error is achieved the value of L (Length of pendulum suspension cord), is an indirect indication the inter-pulse period.

3. Reconstruction

For the reconstruction of the *pulsilogium* A2, we first looked at the A1 to see how our understanding of this simpler version of the instrument might help [Fig. 11].

Pulsilogium A1 consisted simply of a hand-held pendulum and measuring rod. Having synchronised the swing of the pendulum with the patient's pulse at two pulse strokes per pendulum cycle, the length of pendulum cord was measured with the measuring rod; this measurement was then recorded to represent the range of the pulse.

Although based on the same principle, the A2 beam and scale are horizontal and the scale range is now 10 to 80 rather than 0 to 80. In the A2, thread length is adjusted by means of a tapered peg. At this early stage of the reconstruction process, the only available illustration we had of this instrument was a woodcut drawing showing very little detail [Fig. 12].

3.1 Comparing Existing Replicas

To refine our ideas about design and materials we collected visual evidence by consulting replicas of the A2 found in at least four European museums that are listed below:

Replica	Figure	Type	Location
1	[Fig. 16]	Pulsilogium A2	Boerhaave Museum (Leiden)
2	[Fig. 17]	Pulsilogium A2	Museum of History of Medicine, MusMe (Padua)
3	[Fig. 18]	Pulsilogium A2	Museum of History of Medicine, University of Rome 'La Sapienza' (Rome)
4	[Fig. 19]	Pulsilogium B	Laboratory of the Department of Physics, University of Pisa (Pisa)

While useful from the general viewpoint of studying design and approach, a careful survey of these models quickly revealed that none of them were meant to be historically accurate reproductions; given their lack of both precision and historically informed criteria none of these replicas are faithful to Santorio's original description of *pulsilogium* A2. Almost all of them feature either no scale, or their scale is obviously wrong being assigned incorrect intervals sometimes assuming Santorio's dependence on Galileo's studies. Replica No. 4, for instance [Fig. 19], although similar in overall appearance to pulsilogium B1, is completely inconsistent with all historical references, for it not only assumes a direct reading of pulse rate in beats per minute (evidenced by the non-linear scale-shape), but its construction does not correspond to any historical account.

A further problem to be resolved was deciding on the correct orientation of the horizontal beam. Replica 2 [Fig. 17], shows the thread and bead on the uppermost face of the beam. In Replicas 1 [Fig. 16] and 3 [Fig. 18] however, the broad face of the beam is upright with thread and bead on one side. By drawing from a variety of historical sources but also from practical application our research has confirmed beyond reasonable doubt that, in use, the broad face would have been horizontal i.e. laid flat with the scale uppermost.

Figure 16. Replica 1
Pulsilogium with vertically angled beam, no scale and arbitrary dimensions.

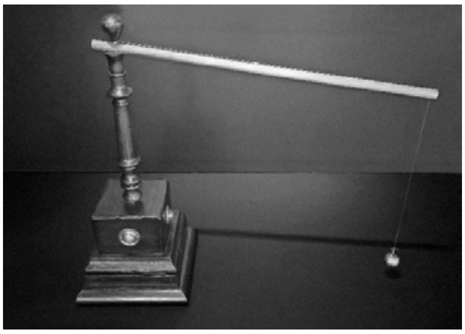

Figure 17. Replica 2
Pulsilogium with horizontally angled beam, no scale and arbitrary dimensions.

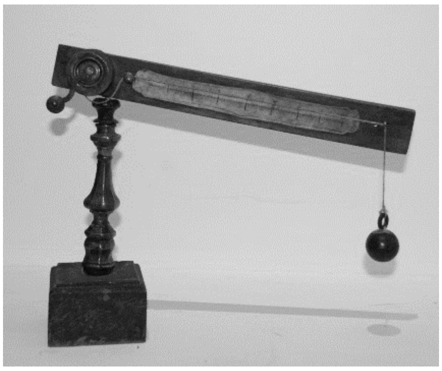

Figure 18. Replica 3
Pulsilogium with vertically angled beam with fake scale and arbitrary dimensions.

Figure 19. Replica 4
Vergara-Caffarelli's model for an alleged 'Galileo's pulsilogium'. Design of this pulsilogium does not correspond to any historical account.

Relying on the design of Marci's *pulsilogium* as portrayed in the frontispiece of his *De proportione motuum* [Fig. 20a-b] it was in fact clear that, in order to be readily useful, the instrument could not have been arranged vertically when in use [as in Figs. 16 and 18], an assumption that we further corroborated empirically. Indeed, operation of the pendulum with the beam in vertical orientation would be severely hampered by friction from an additional 90 degree bend in the thread and the thread being in contact with the rear face of the beam as shown at Fig. 21(a) below, a problem that can be solved by simply laying the beam horizontally as shown in Fig. 21(b).

Figure 20a. Frontispice of Jan Marek Marci *De proportione motuum* (Prague: 1639)

Figure 20b. Detail from Marci's frontispiece showing a portable version of the *pulsilogium* with the beam angled horizontally.

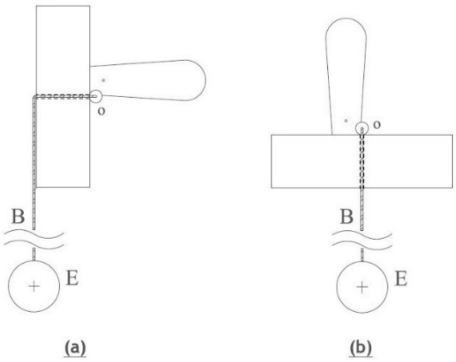

Figure 21a-b. Pulsilogium A2 - Orientation of the beam

It is also relevant to note that, in respect to A1, A2 introduced changes to improve repeatability, avoid interferences, and make operation less cumbersome. One of the defining characteristics of the A2 was in fact that it allowed swing rate to be adjusted and cord length read whilst the pendulum was still in motion. For instance, arranging for the pendulum pivot-point to be independently supported rather than hand-held removed error resulting from oscillation of the pivot-point as the hand was periodically pulled out of position by the swinging weight. As a result, we interpreted Santorio's engraving in Fig. 12 as representing the instrument in perspective, to allow the reader to grasp the overall functioning of the instrument, although it is also possible that, mounted on a wall, the instrument was used horizontally during measurement but inclined vertically afterwards (by means of a pivot connecting the beam to the wall) to allow the physician to have a clear reading whilst taking the pulse of his patient sitting down.

The abovementioned replica no 4 [Fig. 19], deserves particular attention. This is the Vergara-Caffarelli device which is supposed to be a replica of a Galileo's *pulsilogium* as reported by Vincenzo Viviani. And yet, since neither Galileo's nor Viviani's surviving works show either a drawing or a single reference to the *pulsilogium*, it is clear that the overall design for this replica was taken from Santorio's *Commentary to Avicenna's Canon*. Despite being constructed by a competent and skilful physicist, the overall design of this replica is historically and technically flawed. From a technical point of view, it assumes that the pulsilogium type B consisted of simply a thread wound around an axle attached to a pointer which moves over a fixed dial. As anticipated earlier [2.4], however, it is clear from Fig. 13 that the design must be much more complex as its function depends also [B1] on the ability to rotate the dial relative to the frame. Of the two, however, the most important is the historical flaw, inasmuch the replica is equipped with a non-linear scale. As we have already shown, a division of the *pulsilogium* scale into beats per minute not only runs contrary to all the historical evidence found but would have been of no practical use to any early seventeenth-century physician, accustomed to detect great variation in pulse frequency without the help of any instrument.

3.2 Assumptions

Since examination of existing replicas proved them to be historically and technically inaccurate, we decided to go back to the texts and set out some principles which our replica should follow based on three assumptions:

a) Homogeneity between past and present in accounting for an adult pulse rate range, that is to say 60 to 100 beats per minute (bpm);

b) The measurement of the average healthy pulse frequency was taken each time from the approximate central range of the scale [as shown in Fig. 12];

c) In order to avoid the use of a much longer pendulum (too unwieldy for practical use), Santorio counted two pulse strokes per pendulum cycle.

Assumption a) is historically supported by the experiments of Johannes Kepler related in the introduction.

Assumption b) is backed by the fact that Santorio pre-assessed the patient's pulse on a qualitative-diagnostic basis and measured preferably healthy men at rest, resulting in a middle position over the beam.

Assumption c) results from pre-assessment of the instrument application as referred to the average healthy pulse.

3.3 Outline Design and Materials

Materials have been chosen based on clues deriving from Santorio's quotes, and although many of them did not present particular problems (being just paper, thread and wood) we have been compelled to use brass instead of lead for the swinging ball, since the use of lead is prohibited by the current UK Health and Safety regulations[60].

In his 1625 description [Appendix A, Quotation IV] Santorio refers to a thread [Fig 12, letter B], made of linen or silk, whose length is controlled by being wound around a tapered peg. Furthermore, Fig. 12 shows what appears to be either a knot, or a little wooden bead (Letter O) fixed to the thread over the scale, and a pendulum bob (Letter E) that consisted of a leaden ball. From historical records, and from surviving examples of early 17th Century Italian furniture, we know that Italian cabinet makers commonly used wood such as European Lime (*Tilia vulgaris*), for carcases and frame-work. Being Venetian from Capodistria (today Koper in Slovenia), Santorio also had access to wood from the Croatian forests[61]. Since there is no record of the actual wood used to make the beam and a suitably sized piece of English light oak was available, that is what was used in the first reconstruction[60].

A similar historical approach has been adopted in selecting material for the pendulum bob[62]. Although the weight and dimension of the ball does not affect the pendulum isochronism, a historically accurate replica must take into account these details. In estimating the size of the bob from what is known of other components, we realised that it could not have been pistol shot because that would be too small; therefore, it is most likely that a musket ball was used[63]. Santorio himself uses the term *pila plumbea* (leaden bullet) to refer to gunshot wound, and we also know from archaeological evidence that 17th Century musket balls came in a variety of sizes ranging from 16 to 20mm diameter and weights from 22 to 35g depending on the composition of the ball. Practical considerations dictate, however, that lighter bobs would be preferred as, in the case of a portable device as the A2 might also have been[64]. In conclusion, this suggests that the pendulum bob should weigh about 30g.

3.4 Dimensions of the Instrument

One of the most serious problems we faced in our attempt to recreate *pulsilogium* A2 was defining the unit of measurement for the length of the scale and beam. As for this aspect, we couldn't rely on any available source so we had to proceed empirically by adapting modern knowledge to ancient problems. A preliminary consideration was that, although Santorio's instrument did not directly measure pulse frequency in beats per minute, the scale used could not be completely arbitrary as the physician was dealing with a phenomenon whose limits, in normal conditions, tend to remain constant. In this sense, we had to draw a distinction between the apparently arbitrary nature of the resolution adopted (that could span either 50 or 100 degrees as shown in Kircher's and Marci's examples), and the nature of the phenomenon to be measured, which demands precise parameters. As a consequence, in order to understand, replicate and subsequently test limits of the instrument, it was essential to determine the overall length of the scale and, from that, the dimensions of the instrument[65]. To that end, and to render the analysis readily understood in modern terms, it is necessary to relate pulse rate in beats per minute, although, where necessary for clarification, conversion back to inter-pulse period will also be made.

To get an idea of the rough dimensions of the instrument, we considered first the normal range of the pulse. The drawing in Fig. 12 shows a scale of 70 divisions/degrees. Working on the assumption that at two pulse strokes per pendulum cycle this scale covers the pulse rate range of 60 to 100 beats per minute, the change in suspension cord length to accommodate that range has to be 643mm [see Appendix B]. Therefore, the interval between adjacent scale divisions is: 643/70 = 9.186mm. Overall length of the instrument is determined by the measurement range and the space required to fit components to control the thread. In order to measure pulse rate in the range 60 to 100 bpm at two pulse beats per pendulum cycle, the change in suspension cord length – and therefore the scale length, is 643 mm. In our reconstruction [Fig. 22] a few cm were added to extend the measurement range slightly.

Tapered peg and thread hole were positioned according to proportions taken from the woodcut image, so overall length was just short of 1.0 m. Although width of the beam is for practical purposes immaterial, in the interests of historical accuracy this dimension was estimated from the proportions in Fig. 12.

A final question might arise as to why, given the nature of Santorio's pursuit – dealing with small variations of pulse rate in a healthy man – the overall instrument encompasses such a long range. The answer lies in what Santorio and his followers relate as an actual use of the *pulsilogium*. The Venetian physician states in fact that '[t]he instrument shows *all the differences* in equal movements starting from the slowest up to the fastest' [Appendix A, Quotation I], which means that it could account at least for the entire range of the 'latitude of health' (*latitudo sanitatis, neutralitatis et morbi*), which is what we felt confident to assume. As seen, this entry by Santorio is confirmed also by later accounts, such as Lauremberg's, who relates the *pulsilogium* being used to explore *omnigena pulsuum discrimina*[66]. Finally, if the assumption made in Section I.5 is solid, then each region of the *pulsilogium* was meant to correspond to a given species of the pulse, whose range was expressed in decimals of degree.

3.5 Applications

Based on Santorio's written records we can safely assume that he designed his instruments so that the bead would be in the middle of his scale when a normal healthy degree of the pulse was measured. To achieve this condition in our recreation, it was calculated that for the pendulum swing to synchronise with two pulse beats per full cycle at 70 beats per minute the distance between the centre of the pendulum bob and the underside of the beam has to be 73cm [see Appendix B]. After adjusting the tapered peg to set this length, the bead was moved along the linen thread to centre-scale and locked in that position. As stated above, in order to cover the normal healthy range, the

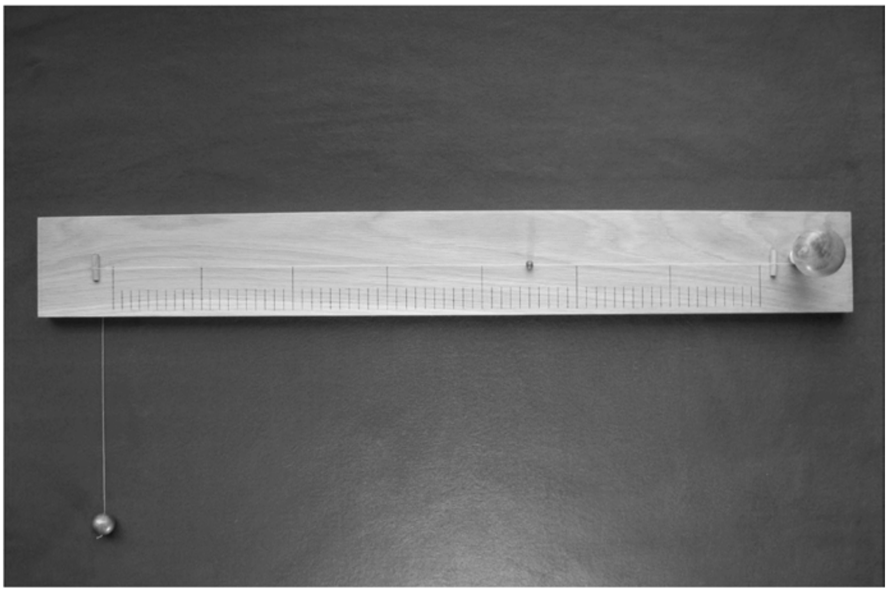

Figure 22. Santorio's Pulsilogium A2 (November 2017)

limits must be at least 643mm apart, this being the required change in cord length to measure between 60 and 100 beats per minute.

3.6 Practical Reliability

As part of a series of public engagement activities, held as joint events between the Centres for Medical History and Biomedical Modelling and Analysis of the University of Exeter, Dr Joanne Welsman and David Taylor conducted a series of tests to address the question of how reliable was the *pulsilogium* in terms of practical measurements. Some of these tests took place at the Honiton Festival of Imagination (2016) whilst others at the South Devon University Technical College (SDUTC) in Newton Abbot (UK). In the latter, measurements were taken by students with no background in early modern medicine, using replicas of Santorio's *pulsilogium* A2. Students took measurements in a kind of doctor-patient session, whereby two different students (doctors) were asked to use our replica 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 acknowledged, overall however, it turned out that the difference between measurements was negligible and almost exclusively attributable to the ability of the student taking the measurement to match pendulum swing to pulse rate.

4. Conclusion

This article presented a series of evidences drawn for the most part from a method of threefold analysis, historical-intellectual-experimental. In the first part we directed our attention to the historical and intellectual background of Santorio's *pulsilogium*, by presenting a series of testimonies, most of them unpublished or not previously discovered. The result of this lengthy research, led us to argue that Santorio's *pulsilogium* does not result from, but rather reawakened, Galileo's studies on the pendulum. The intellectual impact of this conclusion for the history of ideas and science might be important as there is room to reclaim a certain continuity between late Scholastic and early modern mechanics – as especially developed within the so-called Venetian Aristotelianism – in terms of reassessment of ongoing problems rather than conceptual revolutions or paradigm shifts. This is further corroborated by the fact that, despite Viviani's and some early modern scholars claim, throughout the seventeenth and the early eighteenth century the *pulsilogium* continued to be used as a comparator of degrees and that, despite Ammonton's and Floyer's attempts, only in the early nineteenth century would a more reliable measurement of the pulse be made available. From this standpoint, we further proved that Santorio never intended the pulsilogium to be used to make absolute measurements of pulse rate and that, when used as a comparator A2 gives an extremely reliable indication of very small changes between successive measurements. The measurement of small variations as opposed to great ones, was in accordance with Santorio's understanding of physiology as the variability of a certain condition within a given parameter, something that we call today homeostasis, a concept Santorio clearly helped to shape by means of his quantitative experiments on weight, pulse, and temperature. Historical evidence further suggests that measurement with the *pulsilogium* required a qualitative pre-assessment of the pulse in terms of the standard Galenic medicine available at the time. Therefore, when assessing the progression of illness in any particular patient, Santorio used the *pulsilogium* to compare different values in terms of added or subtracted degrees which results in a series of rapports between different degrees taken at various stages of the diagnosis. This led in turn to assign an exact range for the Galenic theory of the pulse and its terminology. The resulting measurement would show the 'latitude of the pulse' corresponding to the Galenic articulation of 'latitude of health', that is to say its variation in healthy/unhealthy conditions, allowing a physician – for the first time in the history of medicine – to monitor the homeostatic balance of an individual and to draw diagnostic indications of their health with unprecedented precision.

Acknowledgements. The historical and intellectual research for this paper was funded by a Wellcome Trust Fellowship (WT106580/Z/14/Z) awarded to Dr Fabrizio Bigotti in February 2015. However, recreating Santorio's *Pulsilogium* A2 has constituted a collective endeavour which will undoubtedly require many further adjustments and discussions. We will keep experimenting, aiming at reconstructing all Santorio's instruments in the forthcoming events of "The Laboratory of Santorio".

We are particularly grateful to the MAGPIES Group, led by Dr Joanne Welsman, who effectively contributed towards the understanding of Santorio's programme of quantification in medicine by organising and holding a series of public engagement seminars at the University of Exeter, and to Prof. Jonathan Barry, Co-Director of the Centre for Medical History (CMH) of the University of Exeter, for the continuous support and encouragement he offered throughout the project. We are equally grateful to Prof. John Wilkins, Emeritus Professor of Classics and Ancient History, who carefully revised the Latin translations in Appendix A.

Whilst the final version of this paper was being prepared and after it had passed a double peer-review, Sue Waring, a talented mathematician and an enthusiastic member of our group of experts, passed away after a short illness. Throughout the making of the "Laboratory of Santorio" Sue has often been insightful and her challenging of our common assumptions on early modern mechanics has led us to pursue more in depth solutions. We like to think that, somehow, a part of her will live on in this article to whose memory it is gratefully dedicated.

APPENDIX A

Text and Translations

Q I Methodi Vitandorum Errorum Omnium Qui in Arte Medica Contingunt Libri XV (Venice 1603)

ff. 109rD - 109vB

Quocirca si ex pulsibus aliquid divini in arte medica colligere volumus, duo mihi videntur severe observanda: alterum est, ut illa tantum arcana pulsuum praecognoscamus, quae per se et proprie cuilibet speciei pulsus conveniunt: alterum est, ut in applicatione, et (ut aiunt) in actu practico sciamus exacte conferre pulsus praeteritarum accessionum cum pulsu praesentis; quoniam solum ex hac collatione certum et infallibile iudicium colligemus, an aeger sit in meliori, vel deteriori statu; solet enim medicus aliquando invenire pulsum sani hominis adeo inaequalem, intermittentem, et aliis deterrimis conditionibus donatum, ut medicus, qui alias non tetigerit, et observavit, in cognitione, et curatione caecorum more incedat: esset igitur operaepretium in sanis hominibus semper motum praecipue observare, quia in aegritudine longe melius crebritatem pulsus, et caeteras conditiones metiri, et certo scire possemus, quantum recedant a naturali statu possemusque omnes proportiones observare, et intermittentiam, si adest dimetiri, et plura alia ad motum pertinentia: pro qua cognitione exacte, et cito comparanda instrumentum pulsilogium invenimus in quo motus, et quietes arteriae quisque poterit exactissime dimetiri, observare, et firma memoria tenere, et inde collationem facere cum pulsibus praeteritarum dierum; exhibet enim instrumentum omnes aequalium

Thus, if in the art of medicine we wish, with regard to the pulses, to obtain something of the divine, I believe that we must strictly heed two things: the first is that we presuppose only those 'general notions'[67] of the pulse that are applicable 'per se' and 'precisely' to whatsoever species of the pulse it might be; the second is that we should know in the application and – as they say – in practical action how exactly the pulse of the previous measurements compare with the present pulse. For only from this comparison can we obtain a certain and infallible judgement on whether the patient is in a better or worse condition. Sometimes, in fact, a doctor is accustomed to find the pulse of a healthy man inconstant (*inaequalis*), intermittent (*intermittens*) and provided with such unfavourable conditions that, like a doctor who has not touched and observed other conditions, he advances like the blind, both in understanding and cure. It should therefore be important to observe on all occasions above all the movement <of the artery> in healthy men, because in sickness, we can measure much better the velocity and other conditions of the pulse and gain certain knowledge of the exact measure of the distance from the natural state; and we can observe all the proportions and measure intermittence if present, and many other things that motuum differentias, quae sunt centum et triginta tres incipiendo ab osservatione rarissimi motus usque ad creberrimum, cur autem non sint plures, in proprio libro *De instrumentis medicis non amplius visis* Deo fovente declarabitur: totidem observantur differentiae [in]aequalium motionum; ex cuius pulsilogii observatione primo colligimus qualibet die, et hora quantum aegri recedant in crebritate a statu naturali, secundo infallibilem notitiam praebet, qua hora desinat augmentum, incipiatque status, et declinatio: tertio observatur virtute proportionum aequalium motionum in pulsilogio observatarum, quam crebritatem, quam intermissionem, et quietem externam quolibet individuum perpeti, et non perpeti potest: quarto metiri possumus quietem diastolis, et quanta sit quies externa, qua cognita, illico morbi magnitudo, et cachoetiae vehementia praecognoscuntur; postremo quilibet sensatus medicus intermittentiam cognoscet, an scilicet arteria per unum ictum quiescat, vel per duos, an per uni-cum cum dimidio, vel cum tertia ictus parte, vel quarta, et sic usque ad decimam, quae sine instrumento est prorsus impossibile, dimetiri; sed quia in proprio libro de hac re sumus acturi, non est, ut omnes instrumenti usus referam [...].

pertain to the movement. In order to obtain that exact understanding and quick comparison I invented ‘a device that measures the pulse’ (*pulsilogium*) by means of which everyone can exactly measure the movement and the rest of arteries, observe and firmly remember, and subsequently make a comparison with the pulses of the previous days. The instrument shows in fact all the differences of equal movements, which are 133 starting from observation of the fewest up to the fastest movements; why they are not more numerous I will declare, with the assistance of God, in my book *Medical instruments no longer seen* – so many are the differences of equal movements that one can observe. From the observation of this *pulsilogium* we collate first and foremost on whichever day and hour it might be how far the patients depart from their natural state in terms of velocity; secondly, the *pulsilogium* provides an infallible note of the hour in which the increase ceases and the stationary state begins, as also the decline; thirdly, by virtue of the proportions of equal movements that are observed in the *pulsilogium*, it is possible to observe what velocity, what intermission and what external rest each individual is able or not to sustain; fourthly, we can measure the rest of the diastole, and the extent of the external rest: once this is known, the greatness of the disease (*magnitudo morbi*) and the vehemence of the bad disposition can be readily predicted. Finally, the skilled doctor will recognize the intermittence <of the pulse>, that is to say whether the artery rests for one stroke or two, or for one and a half, or one and a third or fourth part of a stroke, and so on up to the tenth; something that, without the instrument, it is absolutely impossible to measure; but since we will discuss this topic in our book, there is no necessity now to show all the uses that such an instrument is capable of [...].

Q II Commentaria in Artem Medicinalem Galeni (Venice 1612)
Pars III, col. 374E-C

[...] <Galenus> nos docet, quomodo dimetiri possimus quantitatem, et vehementiam caliditatis, vel frigiditatis intemperaturarum; dicitque tantam fore intemperiei quantitatem, seu vehementiam, quantus est recessus a statu naturali [...]. Nos utimur quattuor instrumentis, quibus reddimur certi de quantitate recessus; quorum primum est pulsilogium a nobis inventum, quo quotidie quantum quis recedat ab optimo suo statu cognoscimus; secundum, idem cognoscimus per motum pilae plumbeae pensilis filo, qua quisque filo commota, et magis, vel minus elongata observare poterit naturalem pulsus motionem, et recessum a naturali; verum nos mira industria ex pulsilogio dimetimur motus, et quietes arteriae, collationemque facere possumus cum pulsibus praeteritorum dierum [...].

Galen teaches us how we can measure the quantity and strength of hot and cold in intemperate mixtures. He states that the quantity or the strength, of the intemperate mixture will be as much as its distance from the natural state [...]. I make use of four instruments by means of which I ascertain the quantity of this distance. The first one is an instrument that I invented and is called *pulsilogium*, through which we grasp how much in each day each individual departs from his best condition. The same result is provided by the second instrument, by means of which, by putting in movement a leaden ball attached to a suspended thread and, from its movement on the thread, and from the greater or smaller lengthening, anyone will be able to observe the natural motion of the pulse and its distance from the natural. By means of the *pulsilogium* I measure with great diligence the motion and rest of the artery and I can also compare this measure with the pulse of the previous days [...].

Q IIIa Commentaria in Primam Fen Primi Libri Canonis Avicenna (Venice 1625)
coll. 21C-22B

Primum est nostrum pulsilogium, quo per certitudinem mathematicam, et non per coniecturam dimetiri possumus ultimus gradus recessus pulsus quo ad fre-

The first instrument is our *pulsilogium*, by means of which we can measure with mathematical certainty and not by conjecture the utmost degree of how much the pulse <departs from the

quentiam, et raritatem: de quo instrumento aliquid diximus lib[ro] 5 Meth[odi] nostrae. A dicto pulsilogio desumpsimus hoc paratu facile, quod explicatur per primam figuram (ut infra) quae continet funiculum ex lino, vel serico contextum, cui (ut vides) appensa est pila plumbea, qua impulsa, si funiculus est longior, motus pilae fit tardior, et rarior: si brevior, fit frequentior, et velocior. Dum igitur volumus frequentiam, vel raritatem pulsus dimetiri digitis impellimus pilam laxando, vel contrahendo funiculum usque eo, quo motus pilae omnino conveniat cum frequentia, vel raritate pulsus ipsius arteriae; quo adinvento illico e regione observamus gradum 70 ostensum a linea alba ipsius pilae ubi est C: quo gradu memoriae consignato, iterum eadem, vel sequenti die eodem instrumento experimur, an pulsus arteriae factus sit aliquantum frequentior, vel tardior: dicimus aliquantulum: quia usu istius instrumenti non quaerimus pulsus notabiles raritatis, vel tarditatis differentias, quas medici memoria tenere possunt: sed illas minimas, quarum differentiae inter unum, et alterum diem non sunt scibiles. In eundem usum est aliud simile instrumentum, cuius iconem videbis fol[io] 78 figura E. At notandum, quod pila plumbea per maiorem, vel minorem vim impulsa non mutat raritatem seu frequentiam: quia in impellendo quantum amittitur de spacio, tantum remittitur de violentia. Per tale instrumentum tempore sanitatis pulsus dimetimur: deinde tempore aegritudinis animadveritmus recessum a naturali statu, qui in affectibus dignoscendis, predicendis, et curandis est maxime necessarius. Ad haec cognoscimus differentiam inter pulsum humilem, et invalidum: in qua re saepe medici decipiuntur, dum confundunt pulsum humilem cum invalido: differentia est, qui

natural state> with respect to frequency and infrequency: on this instrument we said something in the fifth book of our *Method*. From the abovementioned *pulsilogium* we have prepared this simple device, illustrated in the first figure displayed below [Fig. 11], which contains a small rope made of linen or silk, to which (as you can see) is attached a lead ball. When the ball is struck, the longer the string, the slower the movement of the ball and rarer the frequency; contrariwise, the shorter it is, the more it becomes frequent and quick. Hence, if we wish to measure the <major or minor> frequency of the pulse, we have just to put the ball in motion with our fingers, by releasing or shortening the little rope up to the point in which the movement of the ball matches exactly the frequency or infrequency of the pulse of the artery itself. Once it has been found, in that point we should immediately observe the degree, let say 70, indicated by the white line drawn on the very ball where it is the letter C. After keeping in mind such a degree, by using again the same instrument the same day, or the day after we can test (*experimur*) whether the pulse of the artery has been rendered a little bit more frequent, or a little bit slower: I do specify ‘a little bit’ as, by using such an instrument, we do not strive after the discovery of the great differences of the infrequency or slowness of the pulse that any physician is able to keep in mind, but the minimal ones that are impossible to be recognized between one day and another. Another similar instrument has the same application, whose picture you can see in the folio 78 figure E [Fig. 12]. It is quite noteworthy that by pushing the ball a little more or less hard, it does invalidus in febribus non remittit frequentiam: humilis vero remittit, quae remissio, si exigua sit, a medicis sine instrumento non percipitur, et in praedicendo turpiter hallucinantur. Sed de aliis usib[us] suo loco.

not change its frequency nor its velocity, as when the space reduces, the force (*impetus*) decreases correspondingly. By means of such an instrument we measure the pulse when the patient is healthy, subsequently, when he is sick, we notice the distance from the natural state, which is something that is absolutely necessary in order to recognize, foresee and cure the diseases. By means of it we become aware of the difference between the *pulsus humilis* and the *pulsus invalidus*, an aspect in which doctors are often wrong as they mistake the former one with the latter: the difference consists in the fact that, during the fever, the *pulsus invalidus* does not decrease its frequency while the *pulsus humilis* does, and such a decrease, if really small, is impossible to be recognized by doctors without the instrument. Thus in prognosis they get it terribly wrong. But I shall explain other uses of this instrument in another context.

Q IIIb Commentaria in Primam Fen Primi Libri Canonis Avicennae (Venice 1626)

coll. 21D-22 – Padua, Ancient Library Vincenzo Pinali,

Shelf-mark STM.DUCC.VI.F.-2.(FA)

Variants are given in Italics

Primum est nostrum pulsilogium, quo per certitudinem mathematicam, et non per coniecturam dimetire possumus ultimos gradus recessus pulsus, quo ad frequentiam, et raritatem, de quo instrumentum egimus libro 5 methodi nostrae, *quod imprimi non curavimus: quia, nisi ageretur de eius constructione, quod per multas figuras fieret, lectores non intelligerent: ideo de illo esse agendum remisimus in librum De instrumentis medicis, quem, Deo dante, imprimemus, a nostro tamen pulsilogium desumpsimus* <. *Sunt*[68] >

The first instrument is our *pulsilogium*, by means of which we can measure with mathematical certainty and not by conjecture the smallest degree of how much the pulse <departs from the natural state> with respect to faster or slower frequency: on this instrument we said something in the fifth book of our *Method*: *we did not undertake its printing because, if we don't deal with the way to build it which requires many plates, the reader would not understand it. For this reason, in that* *plura instrumenta; inter quae adest hoc commune, quod explicatur per primam figuram: sed in omnibus instrumentis ad eandem rationem pulsus fit frequentior, vel rarior: in meo pulsilogio pulsus fit rarior a maiori rotae portione, frequentior vero a minori. In hoc vero explicato per primam figuram, filum F quod longius est indicat pulsum rariorem: dum vero idem filum abbreviatur, impulsa pila plumbea pulsus fit frequentior: quae raritas et frequentia significatur per gradus, qui in instrumento G respiciunt e regione fili extremitatem, quae est ubi est C. Pila plumbea* per maiorem, vel minorem vim impulsa non mutat *eandem* raritatem seu frequentiam: quia in impellendo quantum amittitur<,> de spacio tantum remittitur de violentia. *Usus plurimi sunt, de quibus suo loco: praecipui tamen sunt, quia per tale instrumentum tempore aegritudinis animadvertimus recessum a naturali statu, qui in affectibus dignoscendis, praedicendis, et curandis est maxime necessarius: vel quotidie dimetiendo pulsum, animadvertimus differentiam inter pulsum hodiernum, et praeteritorum dierum: cognoscimus differentiam inter pulsum humilem,et invalidum: quia saepe medici decipiuntur, dum confundunt pulsum humilem cum invalido:* differentia enim est, quia invalidus non remittit frequentiam: humilis vero remittit, quae remissio, si exigua sit, a medicis non percipitur et in praedicendo turpiter hallucinatur: *cum dicto tamen instrumento exactissime dignoscitur:* sed de aliis usibus suo loco.

context we decided to postpone its explanation to the book 'On medical instruments' which, with the favour of God, we will print. From our pulsilogium, however, we derived many instruments, amongst which there is this common one, which is explained by the first image [Fig. 11]: *yet in all my instruments the pulse becomes more or less frequentfor the same reason. In my pulsilogium, the pulse becomes less frequent when it corresponds to a greater portion of the circle, more frequent when it correspond to a smaller one.In this instrument, explained by the first figure, the wire F, being longer, indicates a less frequent pulse but when the same wire is shortened and the leaden ball is put in motion, the pulse becomes more frequent. The greater or lesser frequency is indicated by the degrees which in the instrument G are about the extremity of the wire, which is, where is C.* If you push the ball a little bit more or less hard, it does not change its *constant* frequency nor its velocity, as when the space reduces the force decreases correspondingly. *There are many uses of this instrument, which will be declared in another place, the most important are that, by means of such an instrument when the patient is sick, we known how much is the distance from the natural state, which is something that is absolutely necessary in order to recognize, foresee and cure the diseases. Another one, is that by daily measuring the pulse we become aware of the difference of the pulse between the present and the past days; we become aware of the difference between the 'pulsus humilis' and the 'pulsus invalidus', as doctors are often misled when they take the former for the latter:* the difference consists in the fact that, during the fever, the *pulsus invalidus* does not decrease its frequency while the *pulsus humilis* does, and such a decrease, if really small, is impossible to be recognized by doctors and when they have to pronounce their prognosis they get it terribly wrong.

With the abovementioned instrument this difference can be exactly evaluated, yet we will explain other uses of this instrument in another context.

Q IV Ivi, coll. 77A-78A

Figura D est pulsilogium quod nos adinvenimur, quo non solum tempus, sed etiam frequentiam, et raritatem pulsus dimetimur, in hoc instrumento sunt septem differentiae frequentioris, vel rarioris motus, quae per radium observantur: deinde quilibet gradus dividitur in septem minuta, quae per radiolum distinguuntur, cuius instrumenti constructionem in lib[ro] *De medicis instrumentis* docebimus. Figura E similiter est mensura; qua exactissime idem observamus. Corda est B, cui affixa est pila plumbea quae est E, qua impulsa, quo brevior est, eo frequentius; quo longior, tardius et rarius movetur.

The figure D [Fig. 15] displays a *pulsilogium* that I have invented by means of which I measure not only the time, but also the greater or lesser frequency of the pulse; this instrument presents seven differences related to movements that are more or less frequent and are indicated by the hand; additionally each degree is divided into seven minutes that are specified by the smaller hand: I will teach how to build such an instrument in the book *Medical Instruments*. Figure E [Fig. 12] likewise is an instrument of measurement by means of which we observe the same thing with absolute exactitude. The Letter B shows the rope to which is attached a lead ball, indicated by E. When you strike this ball, the shorter the rope the more frequent the movement; and the longer the rope the slower and less frequent the movement.

Q V Ivi, col. 219C

Tertium [instrumentum] est ad instar cotylae depressae[69], ex qua egreditur filum, cui appensa est pila plumbea.

The third instrument [Fig. 13] is like a 'concave bowl' from which runs a wire to which is fasten a lead ball.

Q VI Ivi, col. 222C

Sed in observationibus dictorum instrumentorum indicantium temperaturam calidam, et frigidam requiritur utriusque pulsilogii peritia. In tertio, a quo pendet filum,

But for the <proper> observation of the abovementioned instruments, which indicate the cold and hot temperature[70], the mastering of both cui appensus est globulus plumbeus eodem filo longior, vel brevior dimetimur motus tardiores et frequentiores: quanto enim filum longius est, tanto eius moto tardior, ~~et frequentior~~ [*recte* rarior] fit, quanto brevius, tantus eius motus est velocior, et frequentior: maior vero, et minor tarditas, et frequentia dignoscitur per gradus, qui ostenduntur ab indice pulsilogii. Eundem usum praestat quartum instrumentum, quo similiter dimetimur, et temporis spatium, tarditatem, et frequentiam pulsus: itaut quisque his pulsilogiis poterit motum, et quietem pulsus memoriae consignare, indeque collationem facere pulsuum praesentium cum pulsibus sequentium, et praeteritorum dierum. Indeque colligemus quaelibet die, et hora quantum aegri recedant, vel accedant ad statum naturalem. Addimus, quod nullus medicus sit tam foelici ingenio, et memoria, qui posset sine pulsilogio tenere memoria minimas differentias motus, et quietis arteriae: ideo, quod alii medici coniectura de motu pulsuum percipiunt, nos merito pulsilogii, cognitionem infallibilem consequi valeamus.

pulsilogia is required [Figs. 12 and 15]. In the third type [Fig. 12], which is provided with a hanging wire to which a little lead ball is fastened, if I shorten or lengthen the wire I can measure slower or faster movements: the longer the wire, the slower and less frequent its movement; and the shorter it is, the faster and more frequent its movement; the major or minor slowness and frequency are discerned by the degrees displayed by the index of the *pulsilogium*. The fourth instrument [Fig. 15] has the same use and with it I measure in a similar way both the interval of time, the slowness and the frequency of the pulse to such an extent that, by using these *pulsilogia*, anyone will be able to keep in mind the movement and rest of the pulse and subsequently make a comparison of the pulses of the present day with those of the following, or previous days. From <the use of the *pulsilogium*> we gather information on how much, for each day and hour, the patient is departing from, or approaching to the natural state. In addition I want to point out that no physician is provided with such ingenuity and memory to be able, without the *pulsilogium*, to keep in mind the minimal differences of the movement and rest of the artery: wherefore, while the other physicians become aware of the movement of the pulse by conjecture, I by using the *pulsilogium,* can instead reach an infallible knowledge of it.

Q VII Ivi, coll. 364C-365A

Cotyla. Per propositam cotylam habemus modum dignoscendi, an systole pulsus sit velocior diastole, quod ante nos (quod sciam) a nemine fuit inventum: quanti usu

Cotyla. By means of the present ‘bowl’ [Fig. 14] I can discern whether the systole of the pulse is faster than the diastole, something that before me (as sit haec cognitio colligitur ex Galeno cap. 32 Artis medicae ubi agit de corde calido et humido, habet enim haec verba, *in ipsis humoribus corruptis, et putrefactis expirationes sunt maiores, et velociores: et systole arteriae in pulsibus est velox*. Ex systole igitur velociori quam sit diastole Galenus colligit superfluam humiditatem, humoresque corruptos, et putrefactos praedominari. Ergo ubi systole erit velocior quam sit diastole, erit procedendum ex siccantibus: ubi tardior humectantibus: quo ignorato medicus cognoscere ex pulsu non potest, quando sit humectandum, et quandum exsiccandum. Quod quanti sit momenti, nemo est qui nesciat. Modus igitur dimetiendi velocitatem, et tarditatem systoles, (quod est difficillimum, quia systole digitis nostris pulsus tangentibus non occurrit) colligitur ex expiratione, quae si fuerit velocior, velocior erit systole: sic si inspiratio erit velocior, velocior quoque erit diastole. Modus vero dimetiendi inspirationem, et expirationem habetur per instrumentum propositum: dimetimur enim facillime expirationem prius manu ad cor admota, deinde cum filo cui alligatus sit globulus plumbeus satis longo motum et quietem respirationis observamus: dicimus satis longo: quia quo longius est motus tardior fit: quandoquidem inter inspirationem, et expirationem arteria bis, et in multis ter pulsat: satis est igitur, ut sciamus, quod si expiratio sit velocior, quam sit inspiratio, sistole pulsus quoque erit velocior: quia expiratio proportione respondet systole, et ~~expiratio~~ [*recte* inspiratio] diastole: quo praecognito illico ex pulsu colligimus an sit humectandum, vel exsiccandum.

far as I know) wasn't known. How important is such a knowledge can be inferred from Galen's *Ars medica* chapter 32, where he discusses the hot and wet heart; Galen states indeed: *When the very humours are corrupted and putrefied*, *expirations are greater and faster*, *and the systole of the artery in the pulse is fast*. From the systole being faster than the diastole, then, Galen deduces superabundant humidity, and the fact that corrupted and putrefied humours are predominant. Therefore when the systole will be faster than the diastole the treatment will have to proceed by using exsiccant remedies, and when slower by using moistening ones: by ignoring this, no physician can know from the pulse when moistening or drying remedies are needed. There is no one who does not know how important this is. The way to measure the faster or slower frequency of the systole (which is very difficult because the systole does not appear by touching the pulse with our fingers) can be grasped from the expiration that, if faster, indicates that the systole too is faster; likewise in the case of inspiration, which if faster, indicates that the diastole is faster as well. The way of measuring inspiration and expiration is actually provided by the present instrument: indeed we measure the expiration very easily, first of all by putting the hand over the heart, and then we observe the motion and rest of the respiration with a fairly long wire to which a little lead sphere is fastened. The wire must be sufficiently long as, the longer the wire, the slower the motion would be. Inasmuch as between respiration and expiration the artery pulses sometimes twice or even three times in many patients, therefore it is sufficient to know that if the expiration is faster than the inspiration, the systole of the pulse will be faster as well, because the expiration corresponds to the systole, the inspiration to the diastole. Once someone knows this, it will be easy to deduce from the pulse when moistening or drying remedies must be used.

Q VIIIa **Commentaria in Primam Sectionem Aphorismorum Hippocratis (Venice 1629)**
col. 24

Nos diu cogitavimus, quomodo illud quantum morborum interdum percipi possit: excogitavimus quattuor instrumenta, quibus illud dimetimur. Primum est nostrum pulsiogium, quo per certitudinem mathematicam, et non per coniecturam possumus dimetiri ultimus gradus recessus quo ad frequentiam et raritatem [...]

I thought for a very long time how, though only in certain conditions, that very quantity of diseases (*illud quantum morborum*) might be perceived and I invented four instruments, by means of which it is possible to measure that quantity. The first instrument is our *pulsilogium*, by means of which we can measure with mathematical certainty and not by conjecture the smallest degree of how much the pulse <departs from the normal state> with respect to faster or slower frequency

Q VIIIb Ivi, coll. 135-136

Nos tamen diu insudavimus, ut virtutis vitalis quantitatem certa cognitione assequi possimus: invenimusque tria instrumenta, quorum icones proposuimus in *Commentariis nostris supra Avicennam*. Primum est pulsilogium nostrum, quo distinguimus pulsum humilem a pulsu invalido, hoc modo, si pulsus, qui antea fuit vehemens et frequens remittat vehementiam et frequentiam, dicitur humilis, invalidus vero ut plurimum caret hac conditione, quod scilicet fiat quietior: haec maior vel minor frequentia si perexigua sit,

I sweated however for a long time over how to be able to pursue the quantity of the vital virtue with certainty and I invented three instruments whose images I showed in our *Commentary to Avicenna's Canon*. The first one is our *pulsilogium*, by means of which we distinguish the *pulsus humilis* from the *pulsus invalidus* in this way: if the pulse that was previously strong and frequentdecreases its strength and frequency it will be called *humilis*, whereas it will called *invalidus* when it

a medicis sine pulsilogio dignosci non potest.	mostly does not present such a condition, that is of becoming quieter: if the difference between the major or minor frequency is very small, physicians cannot distinguish it without the *pulsilogium*.

APPENDIX B

Initial calibration and measurement of *pulsilogium* A2 scale-shape

Introduction

As has been shown above, our work has established beyond question that Santorio's Pulsilogia were designed and used to indicate what he referred to as "The rest and movement of the pulse", that is to say the time interval between consecutive pulse strokes. The differences between equal and unequal pulses were found by comparing successive measurements, the direction and amount of change helping to assess the progress of the disease. However, in order to facilitate comparison between the performance of this instrument (Pulsilogium A2) and that of its modern equivalents, the following analysis is made in terms of pulse rate in beats per minute.

Initial calibration

Initial calibration setting was calculated using the equation for pendulum period given below.

1. $$T = 2\pi\sqrt{(l/g)}$$

Where:
T = Time for one cycle (period) in seconds (s)
l = Pendulum length from pivot point to centre of mass in metres (m)
g = Gravitational acceleration 9.81m/s^2

As mentioned earlier, it had been decided to place the average healthy pulse-rate of 70 beats per minute near the centre of the A2 scale. Inter-pulse period at 70 beats per minute is:

2. $$\frac{60\ seconds}{70\ beats\ per\ minute} = 0.857\ \text{seconds}$$

At two pulse strokes per pendulum cycle the pendulum period is then:

3. 0.857 x 2 = 1.714 seconds

To find the pendulum length l from this period, equation 1. was transposed to make l the subject:

4. $l = g\,(T/2\pi)^2$

Inserting values gives:

5. $l = 9.81\ (1.714/6.284)^2$

So: $l = 0.7298$m rounded to 0.730m

Accordingly, the tapered peg on pulsilogium A2 was adjusted to make the pendulum suspension cord length from pivot point to centre-mass 73cm. As the scale divisions on this instrument had not yet been decided, a temporary metric scale was fitted with zero at the tapered peg end. This scale was 85cm long, it had already been decided to place the point representing 70 beats per minute pulse rate at centre scale so, taking care not to alter the thread length, the bead reference edge was positioned at 42.5cm from the tapered peg end of the scale. A subsequent check confirmed that the pendulum length was still 73cm.

Relationship between A2 scale values and pulse rate

Having carried out initial calibration as described above, it was decided to record and plot the relationship between scale values and values for pulse rate. Method to be employed was to set the bead reference edge to successive scale points at 5cm intervals, measure and record the corresponding pendulum periods, convert each period into beats per minute then plot a graph of the relationship.

Equipment used:

1. Prototype pulsilogium A2 with temporary metric scale.
2. Tektronix TDS2002C oscilloscope
3. Rare earth magnet 6mm diameter by 1mm thick
4. 2000 turn solenoid with soft iron core 3cm long
5. Stand and clamp to support the solenoid

Initial set-up

Pulsilogium A2 was set in its operating position with its bead reference edge at 42.5cm on the scale.

The small rare earth magnet was attached to the underside of the pendulum bob with Blu-Tac and a check was carried out to confirm that pendulum length from pivot point to centre-mass was 73cm.

Using the stand and clamp, the solenoid was positioned directly under the pendulum bob when it was at rest and the solenoid connected to the oscilloscope Channel 1 input.

Functional check

Pendulum was set in motion and the oscilloscope time measurement cursors used to measure pendulum period by measuring the time interval between displayed pulses. In this case, with the solenoid positioned below the resting position of the pendulum bob the time interval for one complete pendulum cycle is measured between the first and third pulses in the displayed pulse train. It should be noted here that due to the slow time-base rate required to display these pulses, measurement cursors move in 10ms increments. With the pulsilogium at these settings, the calculations above tell us that the pendulum period should be 1.714 seconds. However, the measured value was 1.730 seconds, a difference of 16ms between the calculated and measured value. However, as each cursor moves in increments of 10ms at this time-base rate, this 16ms error is within the measurement uncertainty of 20ms. Even if this were not the case, in terms of pulse rate in beats per minute, the measured cycle time of 1.730 seconds at two pulse strokes per pendulum cycle gives a pulse period of:

1.730/2 = 0.865 seconds

So, the measured pulse rate is:

60 seconds/0.865 seconds = 69.36 beats per minute

Whereas the calculated cycle time of 1.714 seconds at two pulse strokes per pendulum cycle gives a pulse period of:

1.714/2 = 0.857 seconds

Which in beats per minute is:

60 seconds/0.857 seconds = 70.01 beats per minute.

This difference of -0.65 beats per minute is insignificant in terms of physiology but is still an error which had to be accounted for and corrected.

Corrective action

To correct for this offset the tapered peg was adjusted to shorten the pendulum length until the measured period was 1.710 seconds. When measured, the pendulum length from pivot point to centre-mass was found to be 71.3cm. At this setting the bead reference edge was now at 40.8cm from the tapered peg end of the scale. In order to keep the 70 beats per minute point at centre scale the bead was moved along the thread to reposition it at the 42.5cm scale-point. A check of pendulum length confirmed it was still 71.3cm to produce the required pendulum cycle time for 70 beats per minute at two pulse strokes per pendulum cycle.

Measurement of scale-shape

With the tapered peg adjusted to position the bead reference edge at the zero scale-point, the pendulum was set in motion and its period measured and recorded. The tapered peg was then adjusted to position the bead reference edge at the 5cm scale-point and the corresponding period measured and recorded. This process continued at 5cm increments along the scale up to and including the 85cm scale-point.

After the last figures had been recorded a check was carried out to confirm that when the tapered peg was adjusted to position the bead reference edge at the 42.5cm scale point the period was still 1.710 seconds confirming that no settings had changed during the measurements. Data from these measurements were entered into a spreadsheet and values calculated and displayed for pendulum length, pendulum period and pulse rate in beats per minute corresponding to each 5cm step in scale-points.

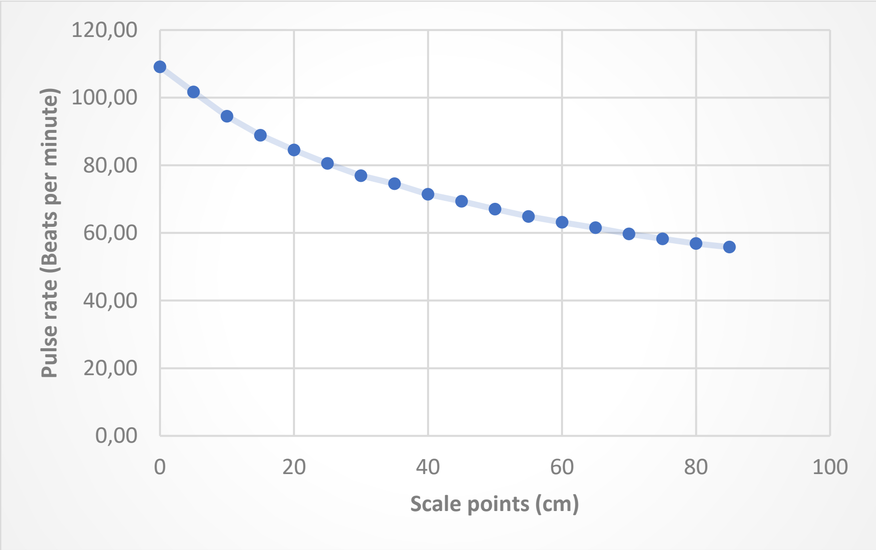

Figure A1. Graph showing the relationship between scale points and pulse rate in beats per minute

Data from which this graph was produced is presented at Table A1 below.

Scale point (cm)	Measured Pendulum period (Seconds)	Pulse rate (Beats per minute)	Pendulum length (cm)
0	1.10	109.09	28.8
5	1.18	101.69	33.8
10	1.27	94.49	38.8
15	1.35	88.89	43.8
20	1.42	84.51	48.8
25	1.49	80.54	53.8
30	1.56	76.92	58.8
35	1.61	74.53	63.8
40	1.68	71.43	68.8
45	1.73	69.36	73.8
50	1.79	67.04	78.8
55	1.85	64.86	83.8
60	1.90	63.16	88.8
65	1.95	61.54	93.8
70	2.01	59.70	98.8
75	2.06	58.25	103.8
80	2.11	56.87	108.8
85	2.15	55.81	113.8

Table A1. Data from measurement of pendulum period.

APPENDIX C

An Assessment of Pulsilogium A2 Precision

Note:

For the same reasons as stated in the introduction to Appendix B above, the following analysis it made in terms of pulse rate in beats per minute (bpm).In this case, as frequency is the reciprocal of time (f=1/t) and vice-versa, the percentage change is the same.

Factors affecting precision

Factors affecting measurement precision of Pulsilogium A2 are:

1. Calibration
2. Synchronisation of pendulum to pulse
3. Reading error
4. Instrument resolution
5. Environmental conditions

Dealing with each in turn:

1. Calibration

This is a two-part process. In the first part the pendulum suspension cord length from pivot-point to centre-mass is set to 73cm. In the second part, a bead or pointer is positioned on the horizontal thread at a point adjacent to the scale-point representing 70 beats per minute (bpm). During this second part it is easily possible to position the bead or pointer to within the thickness of a scale line, so for practical purposes precision of this part can be ignored.

Returning now to the first part, setting the pendulum length to 73cm gives a calculated period of 1.714 seconds. At two pulse strokes per pendulum cycle the pulse interval is then:

1.714/2 = 0.857 seconds giving a pulse rate of 70 bpm.

Assume a measurement error during calibration of 2.0mm. Pendulum length is now:

730 +2 = 732mm making the pendulum period now:

$T = 2\pi\sqrt{(0.732/9.81)}$ = 1.716 seconds

New pulse interval is:

1.716/2 = 0.858 seconds, so new pulse rate is 60/0.858 = 69.930 bpm.

Pulse rate error due to 2mm error in pendulum length is: 70 – 69.930 = -0.07 bpm.

Measurement range of the A2 is 60 to 100 bpm, so span is 100 - 60 = 40bpm.

So: as a percentage of Full Scale, an error of 0.07bpm is: (0.07/40) x 100 = 0.175%FS.

To allow for a 2mm error in the opposite direction the Full Scale error is ±0.175%FS.

2. Synchronisation error

This is dependent upon the skill of the operator. If pendulum swing is not quite aligned with pulse strokes, the measurement will be in error. As no trials have yet been conducted to assess this, it is not yet possible to place an objective figure on this source of error.

However, assuming pendulum bob swing is 30.0cm, even an unskilled operator should be able to adjust the pendulum to match pulse beats to within 0.5cm of each end of the swing. So assume a worst case error of 1cm in 30cm which is (1/30) x 100 = 3.33% error in timing.

As our calibration point is 70bpm, pulse interval should be 0.857 seconds. Adding 3.33% error to this figure makes the new interval 0.8855 seconds. Pulse rate resulting from this error is then:

60/0.8855 = 67.76bpm making pulse rate error: 70 – 67.76 = -2.24bpm. As this error can be in either direction this becomes ±2.24bpm. Expressed as percentage of Full Scale this is:

(2.24/40) x 100 = ±5.6% Full Scale.

3. Reading error

Once again this depends on the skill of the operator but assume a reading error of ±1.0 minor division on the scale. In a reproduction A2 fitted with a metric scale, the error will be ±1.0mm in 643mm (Scale length to encompass 60 to 100bpm).

1 in 643 = (1/643) x 100 = ±0.155% Full Scale.

4. Instrument resolution

Due to the non-linear relationship between scale-points and bpm, instrument resolution changes continuously along the scale. At the 70bpm calibration point resolution is ≤ ±0.8% Full Scale.

5. Environmental conditions

Effect of environmental factors such as temperature and humidity causing dimensional changes to the beam and thread was considered to be minimal so has not been taken into account here. When wood expands and contracts, the dominant change is seen across the grain rather than along it, so percentage change in A2 reading due to this effect will be very small when compared with other uncertainties.

Conclusions

Having now assessed all factors affecting precision of this instrument, and having expressed each of them as a percentage of Full Scale, it only remains to sum them in order to find the maximum error range (Measurement uncertainty):

1.	Calibration	±0.175%FS
2.	Synch	±5.6%FS
3.	Reading	±0.155%FS
4.	Resolution	±0.8%FS

Sum of uncertainties at the 70 bpm Scale-point is ±6.73%Full Scale

Measurement range of this instrument is 60 to 100bpm making its span 40bpm. ±6.73% of 40bpm = ±2.69bpm.

So: When actual pulse rate is 70bpm, instrument reading will be between 67.31 and 72.69bpm.

This is worst-case and assuming an unskilled operator so in practice uncertainty of *Pulsilogium* A2 will be less than this.

Using it in the way Santorio intended makes best use of its repeatability, namely its ability to consistently produce the same swing rate for the same scale set-point. At its best, this can be illustrated by the way Santorio used it to consistently reproduce precise time intervals by setting the position of the bead to previously calibrated points on the scale.

References

[1] Nicole Oresme, *Le livre du ciel et du monde,* I.18, ff. 30a-b; Leonardo Da Vinci, *Codex Madrid I*, ff. 147r, 182r-183r; Giovanni Marliani, *Quaestio de proportione motuum in velocitate* (Pavia: Damiano Confalonieri, 1482), c. 4r; Gerolamo Cardano, *De subtilitate libri XXI* (Basle: Ludovico Lucio, 1554), II, p. 70. A comprehensive history of the use of the pendulum before Galileo is still overdue. A source guide is provided by Drake, S. and Drabkin, I.E. (eds.), *Mechanics in Sixteenth-Century Italy.* (Madison, Milwaukee, London: The University of Wisconsin Press, 1969). A good synthesis on the history of the pendulum and its application is also provided by Lefèvre, W., *Galileo Engineer. Art and Modern science* in *Galileo in Context*, ed. J. Renn, (Cambridge: Cambridge University Press, 2001), 11-28 and Büttner, J., *The Pendulum as a Challenging Object in Early Modern Mechanics*, in *Mechanics and Natural Philosophy before the Scientific Revolution*, ed. W. R. Laird and S. Roux , (Dordrecht: Springer, 2008), 223-238. For the science of motion in late-medieval physics, Clagett, M., (ed.), *Nicole Oresme and the medieval geometry of qualities and motions: a treatise on the uniformity and difformity of intensities known as 'Tractatus de configurationibus qualitatum et motuum'* (Madison: University of Wisconsin Press, 1968) as well as, by the same author, *Giovanni Marliani and Late Medieval Physics* (New York: AMS Press, 1967) although I confess that, in the latter case, I share Randall's disenchantment that the scholar failed to do justice to such an important author.

[2] Galileo himself seems to confirm this in his *Discorsi e dimostrazioni matematiche intorno a due nuove scienze* (Leiden: Appresso gli Elsevirii, 1638), 97, when let Sagredo speaks as follows: ' Io ho ben mille volte posto cura alle vibrazioni in particolare delle lampade pendenti n alcune chiese da lunghissime corde inavvertitamente state mosse da alcuno: ma il più che io cavassi da tale osservazione su l'improbabilità dell'opinione di quelli che vogliono, che simili moti vengano mantenuti, e continuati dal mezzo, cioè, dall'aria; [...] ma che io fussi per apprenderne, che quel mobile medesimo appeso a una corda di cento braccia di lunghezza slontanato dall'imo punto una volta novanta gradi, e un'altra un grado solo, o mezzo, tanto tempo spendesse in passar questo minimo, quanto in passar quel massimo arco, certo non credo che mai l'havrei incontrato, che ancor'ancora mi par che tenga dell'impossibile.'"

[3] Kepler, J., *Epitomes Astronomiae Copernicanae*, Vol. 1, (Linz: Johann Plank, 1618), III.3, 278-279: 'In homine valente, robusto et perfectae aetatis, complexionis melancholicae aut consenescente fere singulis secundis existunt singuli pulsus arteriae (60^o), 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'.

[4] Although his name has almost disappeared from the major scholarship on the history of medicine and science, Santorio Santori (also Santorio or *Sanctorius*) is generally credited with the introduction of quantitative experimentation in medicine as well as for the invention of devices aimed at attaining precision in measurement. He was member of a select and learned group of Venetian aristocrats which included among others Paolo Sarpi (1552-1623) and Galileo Galilei (1564-1642), and was appointed as professor of theoretical medicine at the University of Padua between 1611 and 1624. His major works were the *Ars de statica medicina* (Venice: Niccolò Polo, 1614) which until 1780 saw more than 48 editions with translations in all the most important European languages and the *Commentaria in Primam Fen Primi Libri Canonis Avicennae* (Venice: Giacomo Sarcina, 1625) whereby Santorio presents and partly explains his devices. Santorio's life and his output are largely under-investigated in English, however, the reader will find some useful information in the work of Castiglioni, A., "*The Life and Work of Santorio Santorio (1561–1636),"* trans. E. Recht, *Medical Life* 38 (1931): 729–85 (translation of the original published in Trieste in 1920); Major, R. H., "Santorio Santorio," *Annals of Medical History* 10 (1938): 369–81, and, more recently, Grmek, M. D., *Santorio Santorio*, *Complete Dictionary of Scientific Biography*

(Detroit: Charles Scribner's Sons, 2008), vol. 12, 101–4; Zurlini F. and M. Guidone,"L'Introduzione dell'esperienza quantitativa nelle scienze biologiche e in medicina. Santorio Santorio," in Serrani, A. (ed), *Atti XXXVI Tornata degli Studi Storici dell'arte medica, Fermo, Palazzo dei Priori, 16-17-18 Maggio 2002*, (Fermo: Andrea Livi Editore, 2003), 117–37. Some indications of Santorio's importance in the history of medicine and science can be found in Wear, A., "Galen in the Renaissance," in Nutton, V. (ed), *Galen: Problems and Prospects*, (London: Wellcome Institute for the History of Medicine, 1981), 229–62; Mitchell, S. W., *The Early History of Instrumental Precision in Medicine* (Tuttle: Morehouse and Taylor printers, 1892); Grmek, M. D., *La première révolution biologique: réflexions sur la physiologie et la médecine du XVIIe siècle* (Paris: Édition Payot, 1990), 71–89, a work that, in reference to Santorio, unfortunately contains many major flaws; MacLean, I., *Logic, Signs and Nature in the Renaissance: The Case of Learned Medicine* (Cambridge: Cambridge University Press, 2002).

[5] Micanzio, F., *Vita del Padre Paolo dell'ordine dei servi e theologo della Serenissima Repubblica di Venetia* (Leiden: no editor name, 1646), 211.

[6] Ivi, 225: «...egli si contentò d'un [rimedio] facile, e semplice, proposto dal Signor Santorio, che gl'era antico amico di strettissima conversatione.». An excellent study on Sarpi's scientific thought has been provided by the Italian scholars Cozzi, L. and Sosio, L. (eds), *Paolo Sarpi, Pensieri Naturali, Metafisici e Matematici. Edizione critica integrale commentata* (Milan: Riccardo Ricciardi Editore, 1996), whereby an analysis of Sarpi's idea on motion and weights is discussed in detail (see pp. 111, 408-410). As will be the case with Santorio and Galileo's *De motu*, also for Sarpi the motion of pendulums is conceived in analogy to the inclination of weights over the balance.

[7] Viviani, V., *Racconto istorico della vita di Galileo Galilei indirizzato da Vincenzo Viviani al principe Leopoldo di Toscana* in Galilei, G., *Opere. Edizione Nazionale*, XIX (Florence: Barbera, 1904), 112-121. Viviani's account has rightly aroused scepticism among the most important Galileo's scholars. Drake, S., *Galileo at work. His scientific biography* (Chicago-London: University of Chicago Press, 1978, 20-21), for instance, notes that: 'The credibility of this hotly debated event (viz. Galileo dropping weights from the top of the Leaning Tower of Pisa as a public performance) [...] has suffered not only from such unhistorical embellishments as mentioned, but also from the fact that Viviani was responsible for several palpable errors in chronology about other events relating to Galileo. Thus he placed Galileo's discovery of isochronism of the pendulum in 1583 and even implied that this led him to the *pulsilogium,* a device for timing the pulse, while still a student at Pisa. [...] But it was not until 1602 that Galileo made careful observations of long pendulums, as we shall see, and the *pulsilogium* followed in 1603 as the invention of a Venetian doctor of his acquaintance who made many valuable applications of physics to medicine'. Most recently, Valleriani, M., *Galileo Engineer* (Dordrecht, Heidelberg, London, New York: Spirnger, 2010), 12-13 n26, remarks as follows: 'Vincenzo Viviani also related that, during his third year at the university, Galileo discovered, by means of observations, the isochronism of the pendulum, and that he immediately applied this discovery to the construction of an instrument to measure time while a doctor registers the heartbeat. While there is no doubt that Galileo discovered the isochronism of the pendulum at a certain early point in his life, Viviani's report that he did so in 1584 and thanks to observations of a hanging lamp in the cathedral of Pisa, and that he immediately contrived and constructed that instrument, must evoke scepticism.'

[8] Galileo to Guidobaldo del Monte (Padua, 29 November 1602) in Galilei, G., *Opere,* VIII (Florence: Barbera, 1898), 97-100.

[9] Lomas, D., *Degree of influence on perception and belief and social setting: its relevance to understanding pendulum motion* in *The Pendulum. Scientific, Historical, Philosophical, and Educational Perspectives*, ed. M. R. Matthews, C. F. Gauld, A. Stinner (Dordrecht: Springer, 2005), 297-298.

[10] There is a long-running and well recorded historiographical trend suggesting that the *pulsilogium* should be able to reveal the direct frequency of the pulse as a result of Galileo's alleged discovery

of the theorem of chords before 1602. Since very little has been written on Santorio and his instruments, with the exception of the volume by Grmek, M. D., *Santorio Santorio. Njegovi aparati i instrumenti* (Zagreb: Jugoslavenska Academija Znanosti I Umjetnosti, 1952), 49-54 and the 3 pages article by Levet J., and Agarval, G., "The First man/machine interaction in medicine: the pulsilogium of Sanctorius" in *Medical Instrumentation*, 13/1(1979): 61-63 and nothing on how they actually worked or how to reconstruct them, scholars keep holding and repeating again and again misleading ideas about Galileo's contribution to the pendulum and its application to medicine. This is unfortunately the case of the very recent paper by de Grijs, R., and D. Vuillermin's, *Measure of the Heart: Santorio Santorio and the Pulsilogium*, (Arxiv.org: 2017), 2, where the two scholars assume that the *pulsilogium* was able to provide a direct reading of the pulse rate: 'In developing his pulse meter, Santorio applied Galileo Galilei's insights that the frequency of a pendulum's oscillation is inversely proportional to the square root of its length'. A good example of the misleading application of such an idea has been recently shown by Roberto Vergara-Caffarelli, who claims that the *pulsilogium* has been co-invented by Santorio and Galileo, and has recently rebuilt a replica of the *pulsilogium* for the Department of Physics of the University of Pisa, that is a modification of Santorio's *pulsilogium* B1 but assumes the possibility of a direct reading of the pulse, see Vergara Caffarelli, R., *Il laboratorio di Galileo Galilei* (online publication at: www.illaboratoriodigalileogalilei.it/galileo/: 2005), 40-44. This replica and its flaws will be discussed in Section II.

[11] In many early catalogues of medical books – such as Draud's G., *Bibliotheca Classica*, (Frankfurt: Balthasar Olstern, 1625), 888 and Van der Linden, A., *De scriptis medicis libri duo* (Amsterdam: Johann Blaev, 1637), 427 – an edition of Santorio's *Methodus vitandorum* is reported as published in 1602 *Apud Societatem Venetam*. Since this work contains Santorio's first account of the discovery and application of the pulsilogium, it would be interesting to find a copy of it. Dr Bigotti, who devoted a substantial part of his research to collect original documents referring to Santorio's life and work, has shown that such edition is either a misleading attribution by early scholars or is no longer extant. After the rediscovery of Rudio's quotation, however, such a copy – even if found – would no longer play a pivotal role for the attribution to Santorio but only strengthen it.

[12] Rudio, E., *De pulsibus libri duo* (Padua: Paolo Meietto, 1602) II.1, 23v: 'Sed pro crebritate et raritate dignoscenda unum volo vos admonere, hac scilicet nostra tempestate quoddam instrumentum, quod pulsilogium vocari potest, fuisse excogitatum a Sanctorio Sanctorio medico et philosopho, et omni eruditionis genere praestantissimo, quod quidem admirabile certe est, et huius viri perspicaciae, et ingenii acuminis certum testimonium. Huius enim merito tum arteriae motus et quies exacte dimetiri, et plura alia ad pulsuum dignotionem attinentia adinveniri, tum praecipue praesentium accessio nam pulsus crebritas, et raritas, cum praeteritarum accessionum pulsus raritate et crebritate exactissime conferri possunt.'

[13] Rudio, E., *De pulsibus libri duo* (Francofurti, typis Johannis Spiessi et haeredeum Romani Beati, MDCII). The edition bears the subtitle: 'nunc primum in Germania variegatis characteribus et scholiis marginalibus auctius editi'.

[14] Santorio Santori to Galileo Galilei (9 February 1615) in Galilei, G., *Opere*, XII (Florence: Barbera, 1902), 142.

[15] Bartholin, C., *Problematum philosophicorum et medicorum nobiliorum et rariorum miscellaneae exercitationes* (Wittenberg: Bechtold Raaben, 1611), *Exercitatio Nona*, *Problema* VIII, [page not numbered] Respondente Antonio Fabri. *An pulsum instrumentis dimetiri possimus, et cum pulsu praeteritarum dierum conferre?* Affirmatur: 'Quemadmodum pulsuum doctrina admodum difficilis est et obscura, ita et praxis sphygmica difficultatum non parum abtinet. Quamobrem varii varie ad hanc doctrinam meliore luce illustrandam sese accinxere unicus Sanctorius de Sanctoriis Medicus Venetus, vir uti ingeniosissimus, ita et eruditissimus, amicus noster honorandus, prae

ingenii sui, quo pollet, acumine, Pulsilogium quoddam excogitavit, qua dimetitur exacte arteriae motus et quietes, ut cum pulsu praeteritorum dierum comparatio institui queat. Per hoc organum nonnulla percipiuntur, quae alioquin impossibile est cognoscere; Ut 1. sciri potest cotidie, quantum aegri recedant in crebritate a statu naturali. 2. Qua hora desinat augmentum, et incipiat status atque declinatio. 3. Quam crebritatem, intermissionem, et quietem externam quodlibet individuum perpeti potest, aut non. 4. Metiri licet, quietem Diastoles, et quanta sit quies externa. 5. Cognoscere datur intermittentiam, an arteria quiescat per unum ictum, duos, et c.[aetera]. Quae omnia una cum instrumenti huius utilissimi fabrica uberrime autor ipse aliquando explicaturus est, in libro suo de organis variis medicinae mechanicis, plane dadalicis. Atque utinam fatum hunc suum tam rarum, non diu Reipublica medica invideret. Pulsilogium autem hoc, quod Venetiis amice nobis demonstravit, et particulatim declaravit, habet aequalium motuum differentias centum triginta trium, incipiendo a motu rarissimo ad creberrimum, et tot inaequalium motionum sunt differentiae.'

[16] Lauremberg, P., *Laurus Delphica seu consilium, quo describitur methodus perfacilis ad medicinam* (Lion: Johann Maire, 1621), 29-30: 'De pulsibus ubertim quidem disseruit Saxonia: sed malim pervolas Fernelium, qui brevis est, nec obscurus. Subtilibus enim istis istinctionibus pulsuum, interturbantur potius, quam instruuntur discentum ingenia. Eas ego cum remoris, et impedimentis militiae iuxta aestimare soleo. Qui enim tyro tot differentias discriminet tactu digitorum, quarum vix vigesimam partem, vel auctores ipsi sciunt diiudicare, vel uspiam in homine reperire est. Dico, solo digitorum tactu. [*Instrumentum mechanicum sphygmicum*] Nam instrumentis mechanicis explorari exacte satis possunt omnigena pulsuum discrimina, qualia a Sanctorio excogitata accepimus, et ego unum ex aere meis confectum manibus domi asservo.'.

[17] Santori, S., *Commentaria in primam Fen primi libri Canonis Avicennae* (Venice: Giacomo Sarcina, 1625), *Ad lectorem*: 'In his Commentariis apposui solum illorum instrumentorum icones ruditer, et extempore expressas, quae huic physiologiae respondent: quia audio, discipulos meos in varias terrarum partes dispersos, quos summa caritate, et gratuita benevolentia docui, horum multorum sibi inventionem attribuere, quorum inhumanitas silentio certe non erat obvolvenda.'

[18] On the 1 December 1630 Isaak Beeckman wrote in his *Journal* a note on Santorio which will be discussed in the next paragraph in connection to the physics of the *pulsilogium*; see Beeckman, I., *Journal tenu par I. Beeckman de 1604 à 1634* [Ed. C. De Waard=CdW] III, 174, (1 December 1630). Also Beeckman's famous correspondent, Marin Mersenne (1588-1648) refers to Santorio many times in his works, for instance to Santorio's experiments on body weight, generation of colours and light as well as instruments such as the hygrometer. Furthermore, in his *Harmonicorum Libri* (Paris: Guillaume Baudry, 1636), Mersenne describes the practical application of the pendulum in medicine (that he calls *pulsilogium* possibly in reference to Santorio, see Bk II, Propositio XXVII, 20) and even discusses some problems of Santorio's hygrometer (Bk III, Propositio X, Corollarium 3, 43 wrongly numbered as 52 in the original).

[19] Relevant in this sense is what Santorio's disciple Balthazar Timaeus von Güldanklee (1600-1667) says in his *Epistolae et consilia* (Leipsig: Christian Kirchner, 1677) about Santorio and his instruments: Letter by von Güldankle to Jonas Staudio (Colberg, 6 September 1627), Bk VI, Epistola IV, 848b: 'Instrumenta quidem sua medica seu chirurgica non minus ac mathematica Venetiis monstravit Sanctorius, *sed monstravit, non communicavit praeter illa quorum in commentariis suis super primam Fen libri I Canonis Avicennae meminit*; elegans inter haec est pulsilogium quo frequentiam et raritatem pulsus dignoscimus, et illud, quo aquas hydopicorum per umbilicum educere possumus [...].' Italics are mine.

[20] Santorio's father, Antonio Santorio (ca. 1520-1592/93), a nobleman from Spilinbergo in Friuli, was appointed *bombardiere e sopramassaro* of Capodistria in 1548. Amongst his duties there were the preparation of saltpetre, and to provide supplies, munitions, and proper technical equipment for the Venetian ships in the Adriatic Sea. On Santorio's studies in *mathematics* and music we can

count on a Santorio's letter to Andrea Morosini (1612), on his own remarks in the third part of the *Commentary on Galen* as well as on Arcadio Capello's biography. In the former, Santori, S., *Commentaria in Artem Medicinalem Galeni* (Venice: Giacomo Antonio Somasco, 1612), Pars III, pages not numbered, we read that: 'Quae mutua vicissitudine inter nos fratremque meum Isidorum Sanctorium Iureconsultum a primis aetatulae accrescentis (ut sic dicam) primordiis intercessit familiaris consuetudo, honestis vitae actionibus transacta, *harmonicis musices concentibus in studiorum levamen exercita*, artium libero homine dignarum disciplina indies, et incessanter continuata, linguarum Latialis pariter, et Atticae elegantiae insigniter ornata, gravioribus deinde studiis gradatim adaucta, in eam honoris, et meriti segetem, et ita quidem amplam excrevit, ut nunc uberi cum fenore profundioris doctrinae, *et solidioris sapientiae Matheseos, Philosophiae, et Iatrices* etiam praeconio splendescens, sese palam doctorum undique caetui cum immortali nominis tui gloria ostendat universo, [...].' Italics mine. The same account can be found in Capello's biography, *De vita Cl. Sanctorii Sanctorii*, (Venice: Giacomo Tomasino, 1750), cc. VII-VIII: 'Juvenes ergo non solum hospitio excepit [viz. Giacomo Morosini, Andrea's and Paolo's father] humaniter, verum etiam liberorum numero habere voluit, eosque una cum filiis suis Paulo et Andrea, [...] liberaliter educandos curavit. Studiis itaque ingenuo homine dignis addicti egregiae indolis et summae spei adulescentuli, mirum, quantum brevi tempore nobili quadam aemulatione profecerint. Latis litteri atque Graecis optime inbuti *ad philosophica et mathematica studia incredibili mentis contentione animos appulerunt*.' Italics ours. Further details on Santorio's knoweldge of music are given in Santori, S., (1612), Pars III, col. 131D: 'Adolescentes dilatabunt thoracem, si se exercuerint in edendis magnis vocibus canendo, scilicet vel concionando, vel orando, vel in sono tubae, vel cornicinis se exercendo; ex quorum instrumentorum usu ipsemet aliquando adeptus sum thoracis dilatione.'

[21] Rudio, E., *De naturali atque morbosa cordis dispositione libri tres* (Venice: Grazioso Percacino, 1600), dedicatory letter to Nicolò Contarini [c. 2r not numbered]: '[...] a praeclaro viro Sanctorio Sanctorio, qui ob mirabile et perspicacissimum illius ingenium, ac scientiarum cognitionem, quae ad perfectum philosophum atque medicum pertinent (ut brevi illius scripta in lucem edenda probabunt) unice a te et merito diligitur.'

[22] Caverni, R., *Storia del metodo sperimentale in Italia*, Vol 1, (Florence: G. Civelli, 1891), 304.

[23] Renn, J. and P. Damerow, *The equilibrium controversy. Guidobaldo del Monte's Critical Notes on the Mechanics of Jordanus and Benedetti and their Historical and Conceptual Background* (Max Planck Institute for the History of Science, Berlin: Edition Open Access, 2012), 46-120.

[24] This contradiction regards mostly Aristotle's physics and to a much less extent his mechanics. On Benedetti's approach see Renn, J. and P. Damerow, (2012), 42: 'The proportionality between force and effect, however, seems to contradict experiences gained from levers and balances. Applied to such tools, the same force has different effects depending on the position where it acts on a beam.'

[25] Benedetti, G., *Diversarum speculationum mathematicarum et physicarum liber* (Turin: Eredi Niccolò Bevilacqua, 1585), *De mechanicis*, III, 141.

[26] Benedetti, G., (1585), 142-143, same explanation in Del Monte, G., *Mechanicorum liber* (Pesaro: Geronimo Concordia, 1577), c. 10v: 'Idem ergo pondus propter situum diversitatem gravius, leviusque erit. Non autem quia ratione situs interdum maiorem re vera acquirat gravitatem, interdum vero amittat, cum eiusdem sit semper gravitatis, ubicunque reperiatur; sed quia magis, minusque in circumferentia gravitat.'

[27] On this, Renn, J. and P. Damerow, (2012), 137-142.

[28] Ivi, 108.

[29] Del Monte, G., (1577), Ivi, ff. 13r-v; Renn, J. and Damerow, P. (2012), 111-112: 'Particularly interesting is the case in which the balance is located so that the centre of the world lies at the bottom of the circle described by the balance arm (...). For this case Guidobaldo showed that

the closer the weight is to the bottom the heavier it becomes since, in any other position, it receives support from the balance arm and thus does not attain its full effect. The drawing accompanying the argument shows a circle with various chords connecting points on the circumference with the bottom of the circle; these points are also connected by radii to its centre. Guidobaldo compared the constrained motion along the circumference with the direct motion along the corresponding chord to the centre of the world located at the bottom of the circle. The exact same constellation of motions would later play a crucial role in Galileo's theory of motion, albeit with a different interpretation (...). It seems that Galileo simply transposed Guidobaldo's cosmological model to a terrestrial situation. The centre of the world located at the bottom of the circle then simply becomes again the lowest point of the motion of the beam of a balance, while the various radii represent positions of the beam at different angles. But what about the chords? In a terrestrial setting they can only be interpreted as inclined planes connecting various points along the circumference with the bottom of the circle. Alternatively, the circle itself could also be conceived as representing the cross-section of a sphere or a cylinder constraining the motion. In any case, the motion of a weight left to itself along the circle, whether constrained by the beam of a balance or the surface of a sphere, would then be the motion of a pendulum.'

30 For Heron's influence on Santorio, see Santori, S. (1625), col. 23 [without letter]. On Heron and the equilibrium problem with some analysis of its influence on modern mechanics see Schiefsky, M. J., *Theory and Practice in Heron's 'Mechanics'*, in Laird, W.R. and S. Roux (2008), 15-49.

31 Santori, S., *Commentaria in primam fen primi libri Canonis Avicennae* (Venice: Giacomo Sarcina, 1626), col. 21E: '[...] sed in omnibus meis instrumentis ob eandem rationem pulsus fit freqentior vel rarior: in meo pulsilogio pulsus fit rarior a maiori rotae portione, frequentior vero a minori'. The copy, discovered in 2015 by Fabrizio Bigotti, presents many variants in addition to the known text (1625) and is preserved in the 'Biblioteca Antica Vincenzo Pinali' of Padua [shelf-mark STM.DUCC.VI.F.-2.(FA)].

32 As pointed out by David Taylor, these chords were made of threads cut from intestines of tortoise and were common in Italy and France. On this see Holder, E. J., "The History of the Catgut," *Postgraduate Medical Journal* 25(1949): 427-433.

33 Beekman, *Journal*, CdW III, 174-175, 1 December 1630: 'Sanctorius Sanctori (cuius opera nunc primum video, excepta eius *Medicina Statica* de qua nonnihil antehac scripsi) in *Commentariis in Primam Fen Avicennae* occasionem praebuit mihi, cogitandi cur nervi aut chordae testudinis factae in fine tam celeriter quam in principio aut potius in principio tam celeriter quam in fine, suum cursum sive ictum perficiant, cum in principio multa plus viae sit peragrandum; quaeque sit ratio proportionis inter magnitudinem viae et celeritatem motus in principio et inter parvitatem viae et tarditatem motus in fine. Esto igitur *ae* funis, ex quo pondus *e* pendet perpendiculariter. Idem pondus attollatur in *b;* patet ibi tantam vim habere cadendi *ae* si funi non esset alligatum. Dividatur *be* in duas partes aequales; erit igitur *bac* angulus dimidius recti *bae.* Vis ergo *fb, gc*, deorsum trahens aut ex supernis deorsum pellens, duplo major est in *b* quam in *c*, quia premit duntaxat secundum angulum *ach* qui est dimidius *abt.* Particulae enim quae premunt pondus *c* (cum recta deorsum tendant, pondus vero*c* medio modo se habeat) dimidia tantum virtute sua pondus illud afficiunt.'

34 See for instance Marci von Konrad, M., *De proportione motuum seu regula sphygmica ad celeritatem et tarditatem pulsuum* (Prague: no editor name, 1639), Propositio XL adopts the concept of *libra* to explain the motion of the pendulum. For the defintion "libra sphygmica" see Schott, G., *Magia Universalis Naturae et Artis* (Bamberg: Johan Martin Shönwetter, 1672), Pars III, Bk IV, Pragmatia IX, 320: 'libra sphygmica'; Leupold, J., *Theatrum staticum universale* (Leipzig: Johan Friedrich

Gleditschens Sohn, 1727), 69-71: 'Sanctorii pulse-waag'; Spagnio A., *De motu* (Rome: Arcangelo Casaletti, 1774), 486: 'Libra sphygmica".

[35] Santori, S. (1612), 145C: '[...] probatum est corpora insalubria esse corpora insalubria simpliciter semper, et haec contineri quoque in latitudine sanitatis, quamvis in infimo gradu [...].' See also149D-E: '[...] ostendimusque superius quod insaluberrimum quoque sit in latitudine sanitatis, quamvis sit in infimo gradu [...] insalubria simpliciter, quae sunt infimi gradus sanitatis.'

[36] On the concept of latitude of forms and quantification of qualities see Maier, A., *Zwei Grundprobleme der Scholastichen Naturphilosophie. Das Problem des Intensive Grosse. Die Impetus theorie* (Rome: Edizioni di Storia e Letteratura, 1968), 3-109; Clagett, M., *Nicole Oresme and the Medieval Geometry of Quality and Motion. A treatise on the Uniformity and Difformity of Intensities known as 'Tractatus de Configurationibus Qualitatum et Motuum'* (Madison: University of Wisconsin, 1968); Sylla, E., "Medieval Concepts of the Latitude of Forms. The Oxford Calculators" *Archives d'Histoire Littéraire du Moyen Age* 48(1973): 223-283.

[37] Santori, S. (1612), Pars III, 9A '[...] morbus nihil aliud est ex Galeno 9 methodi medendi cap. 14 quam recessus a sanitate, numquam igitur intelligemus quantus sit recessus, nisi praecedat sanitatis cognitio. '

[38] Appendix A, QI: '[...] esset igitur operaepretium in sanis hominibus semper motum praecipue observare, quia in aegritudine longe melius crebritatem pulsus, et caeteras conditiones metiri, et certo scire possemus, quantum recedant a naturali statu [...].'

[39] Santori, S. (1612), Pars III, col. 10A: '[...] omnia enim corpora quamvis saluberrima, mixta sunt ex quattuor elementis, suntque obnoxia perpetuis alterationibus, dum vero alterantur recedunt, vel accedunt ad saluberrimum punctum; ideo semper indigent conservatione: causa vero conservatrix istius corporis corrigit, sed parvos aliquos prolapsus, sed non sensibiles, ut docet Galenus librum ad Trasybulum cap. 20.'.

[40] Ivi, coll. 71A-72A: 'Ego tamen in mea statica medicina post longam observationem inveni in corpore moderatiori, in quo coctiones, et non corruptelae sunt, crassa excrementa primae coctionis respondere ingestis in vigesima proportione circiter[40]: si ingesta per hypothesim fuerint centum unciarum, alvi faeces si fient compactae, erunt quinque ad summum: de liquidis faecibus nil dicimus, quia sunt praeter naturam. Lotium respondebit in quadrante, verbi causa si ingesta fuerint centum unciarum lotium erit triginta trium unciarum circiter: varietas tamen dependet; propterea quod variae sunt naturae, anni tempora, et aetates: insensibilis vero perspiratio, ut ostendemus in staticis theorematibus excedit omnium excrementorum quantitatem [...].'

[41] Kircher, A., *Mundus subterraneus* (Amsterdam: Johann Jansson and Elyseus Weyerstraten, 1665), 51-52: '*Differentia pulsuum arteriae reperire ope fili chronometri.* Fiat primo instrumentum, eo, qui sequitur, modo et industria. Fiat tigillum A B, cuius superiorem superficiem in quotcunque partes aequales divides, v.g. in centum aut 50; tigillumque hoc, divisum supra fulcimentum C D ita effiges, ut loco dimoveri non queat; pes quoque fulcimenti plumbo coagmentatus stabilitatem instrumento, ne vel minimum vacillare possit, inducat. Hoc praestito, accipe chordam eius tenuitatis, cuiusmodi in cheli minori, minima esse solet, hanc per foramina A et B in extremitatibus tigilli facta ita transfiges, ut affixis in utroque extremo chordae E et F ponderibus, chorda pro libitu prolongari aut abbreviari possit, et habebis instrumentum paratum; cuius usus hic est, qui sequitur. Exploramus itaque pulsuum arteriae differentias, quaere primam vibrationem, quae uni pulsi arteriae pro eo tempore respondeat, quod assequeris, alterutram chordae extremitatem prolongando vel abbreviando; si enim pulsus velocior fuerit, chorda abbrevianda erit, si tardior, prolonganda, et hoc pacto procedes, donec vibrationem chordae invenias pulsi arteriae prorsus aequalem, quae sit v.g. A F vel B E; haec enim erit penduli longitudo, cuius una vibratio aequatur uni pulsi, quam diligenter notabis hac industria: in superiori chordae gemmam seu nodum ita stricte, ut non nisi aegre promoveri queat, et hanc gemmam promove supra primum divisi tigilli A B gradum, quadragesimum in R, ea cautela, ne A B chorda in prima sui

longitudine dimoveatur. Si itaque altero die pulsus differentiam scire desideres, tunc prolongando vel abbreviando chordae alterutrum extremum in tantum promovebis, donec eam penduli longitudinem sortiaris, qua una vibratio uni pulsui arteriae respondeat; quo praestito vide, quem gradum gemma in tigillo abscindat; haec enim erit differentia pulsuum inter hodiernum et hesternum diem quaesita. Exempli gratia: sit chordae B E logitudo, quae vibratione sua unum arteriae pulsum, hominis in sanittate optima constituti, adaequet, et gemma quadragesimum gradum in R signet; postero vero die denuo tentas pulsum, et invenis eum velociorem; unde chorda B E abbrevianda est in tantum, donec unam abbreviatae chordae vibrationem, uni praecise pulsui respondere reperias; quo facto vide, quem linea tigilli A B gradum gemma fecet; ponamus autem ex abbreviata chorda gemmam una ex R in G promotam seu retractam, ubi cum 30 gradus abscindat, concludes differentiam pulsus prioris et posterioris diei esse 10, id est 10 gradibus velociorem: si vero pulsus posterioris diei fuerit tardior, tunc chorda A E prolonganda est, donec aequalitatem vibrationis chordae cum pulsu inveneris, et notandum insuper, quem linea tigilli gradum gemma abscindat, et invenies v.g. eam in 50 gradu subsistere; inferes igitur, differentiam pulsus esse iterum 10, id est, pulsum prioris diei a posterioris diei pulsu tardiorem esse 10 gradibus. Haud secus in aliis procedes.'

[42] Struš, J., *Sphygmicae artis libri V* (Basle: Johannes Oporinus, 1555), I.5: 'Sunt quidem re ipsa plures pulsus simplices, quam quindecim, quos iam recensuimus. Sed quidam ex ipsis sunt medico inutiles: quidam utiles quidem essent, sed ab homine tactu cognosci non possunt. Alii vero sunt, qui cognoscuntur a medico, et utiles illi sunt: sed ad priores reducuntur, et comprehendentur in illis. Inutiles sunt pulsus, quos frigidos et calidos vocant. Nihil enim ex iis cognoscitur, quod scire referret, neque iis medici ad prognostica utuntur commode. Qui autem tactu sunt impercettibiles, sunt: plenus, vacuus, gravus, lenis, grossus secundum tunicam arteriae, et tenuis de quibus libro secundo latius dicetur. Qui autem utiles sunt, et imperceptibiles, sed ad priores reducuntur, sunt longus, latus, altus: et iis contrariis, brevis, angustus, humilis. Priores enim tres constitunt magnum, posteriores tres constituunt parvuum [...].'

[43] Santori, S. (1612), Pars II, col. 223D: 'Quare si corpora sunt in perpetua passione, debet quoque medico hanc perpetuam passionem considerare: quia medicus non est similis brutis animalibus, quae supra sensum non ascendunt: debet igitur, si est artifex, et ars sit habitus intellectus, penetrare quae sensus non penetrant. '

[44] Ivi, col. 530C, see also Appendix A, Quotation III: '[...] usu istius instrumenti non quaerimus pulsus notabiles raritatis, vel tarditatis differentias, quas medici memoria tenere possunt: sed illas minimas, quarum differentiae inter unum, et alterum diem non sunt scibiles.'

[45] Floyer, J., *The physician's pulse-watch; or, an essay to explain the old art of feeling the pulse*, in three parts (London: Samuel Smith and Benjamin Walford, 1707), 41-46, 59-66, 185, 302-321.

[46] Ammontons, G., *Remarques et experiences phisiques sur la construction d'une nouvelle clepsidre, sur le barometres, termometres et hygrometres* (Paris: Jean Jombert, 1695), *Avertissment.*

[47] Girard De Villars, L.-M., Boissier de Sauvages de Lacroix, F., *Pulsus et circulationis theoria* (Montpellier: Auguste François Rochard, 1752), 31: 'Non raro summo medicorum opprobrio accidit ut de eodem aegrotante alter medicus pulsum frequentiorem solito, alter rariorem, alter eumdem esse mordicus contendat. Litem dirimere potest aeger qui tali pulsilogio suum statum diversis diei horis cognoscere voluerit. Saltem hoc experimentum non minus ipsi profuturum est quam inanis amicorum confabulatio.'

[48] Santori, S. (1612), Pars III, col. 376 B-C: '[...] sed quomodo medicus vocatus ab aegrotis, poterit scire eorum statum naturalem, cum tempore sanitatis illos non viderit? [...] Ego vero si antea non fuerit mihi notus aeger, usu quatuor instrumentorum propositorum paulo supra (namely, the two types of pulsilogia corresponding to AB and C in our classification, the 'statera medica', and the thermometer) manuducor ad cognoscendum quantus possit esse recessus, et quanta remediorum

dosis: quamvis fatear cum Galeno I <methodo medendi> ad Glauconem in principio, esse impossibile, ut illud ultimum, et specificum quantum a medico penetretur [...].'

[49] Santorio himself refers to A1 as the simplest and handiest version; see Appendix A, Quotation III-IIIa: *instrumentum paratu facile...commune.*

[50] Capodivacca (Capivacci), G., *Opera omnia quinque sectionibus comprehensa* (Frankfurt: Paltheniana, 1603), *Tractatus de pulsibus*, 190-191.

[51] Drake, S., "Galileo's 1604 fragment on falling bodies (Galileo Gleanings XVIII)" *The British Journal for the History of Science* 4/4 (1969), 346: 'Some find it strange that Galileo should have gone on using expressions like "degree of tardity", and explain this by saying that he was still rooted in the meaningless physical distinctions of Aristotle. But it would be equally tenable, and more illuminating, to say that Galileo's terminology often reflected his mathematics, which was that of the Euclidian theory of proportion. Under that theory, on which Galileo lectured at Padua, and on which he composed the work from which the foregoing quotation was taken, it was impossible to conceive of velocity as the ratio of space traversed to time elapsed. No ratio whatever was allowed to exist between two things different in kind. That is of the utmost importance in any reconstruction of Galileo's thought. To him, velocity was not a ratio, but a "degree of speed", something that was measured by a pure number, just as time and space were measured. The numbers measuring degrees of speed could be added and subtracted, just like those measuring time or space. Ratios could be formed of velocities, and such ratios could be compared with ratios of spaces, or ratios of times, or of numbers, or of lines, or of areas, or ratios of anything else; but both terms of any ratio had to represent measures of the same kind of thing.'

[52] Santori, S., *Commentaria in Artem medicinalem Galeni* (Venice: Marco Antonio Brogiolo, 1630), Pars II, Cap. LIII, col. 762D [this part is not displayed in the 1612 version]: 'Nos per instrumentum vitreum quo dignoscimus temperamenta: excessus et medium cognoscimus hoc modo: spherae instrumenti vitrei nivem applicamus ut aqua ascendat ad ultimum excessum. Deinde flamma candelae curamus ut aqua descendat ad ultimum terminum. Cognitis extremis statim dignoscimus medium et temperatum, a quo quantum quaelibet pars recedat, erit cognitu facilis.'

[53] Marci is quite clear that the overall resolution of the instrument could be made as specific as anyone liked, suggesting that the longer the beam, the better would be the resolution, allowing the physician to account for the smallest differences in pulse frequency, see Marci von Konrad, M. (1639), Propositio XXXXI, Problema II: 'Regula haec nullo apparatu, sed hac arte simplici confit sive ex ligno, sive ex quaelibet alia materia. Huius longitudo *ab* unius cubiti, aut ad placitum: quo enim maior, eo plures differentias tarditatis indicabit: nam ad velocitatem summam indicandam quaelibet magnitudinem sufficit.'.

[54] This passage has not been translated as the translation itself is at stake here; the reader will find an English version of it in Appendix A, Quotation I.

[55] Santori, S. (1612), col. 420A-B. Even clearer on this point Rudio 1602, I.7, 11v: 'Si vero de pulsuum aequalitate, et inaequalitate loquamur, hae imprimis aut simpliciter seu absolute dicuntur; vel certi alicuius generis. Aequales igitur absolute, seu simplicter pulsus sunt, qui neque magnitudinem, neque celeritatem, neque frequentiam seu crebritratem, neque vehementiam, neque mollitiem immutant, sed in ipsis omnibus perseverantes sunt. Illi vero qui in his omnibus immutati sunt, et a prioribus diversi, nec perseverantes in suo pristino statu inaequales absolute, seu simpliciter dicuntur.'.

[56] See n. 48 above, and the already mentioned letter to Galileo n. 14 (notably Galilei, G., *Opere,* XII, 142).

[57] In modern medicine pulse rate is expressed in beats per minute (bpm). The normal range for healthy adults at rest is between 60 and 100 bpm. When expressed as the time interval between

pulse beats the normal range is from one second at 60 bpm, to 0.6 of a second (600 ms) at 100 bpm. Depending on the patient's condition however, pulse rates can range from below 20 to over 140 bpm; in time intervals this ranges from 3 seconds to 428 ms.

[58] See Kircher in footnote 41.

[59] Levett, J., and Agarwal, G., *The First Man Machine Interaction in Medicine: the Pulsilogium of Sanctorius* in *Medical Instrumentation, Journal of the Association for the Advancement of Medical Instrumentation*, 13/1, 1979, pp. 61-63.

[60] In particular COSHH (Control of Substances Hazardous to Health) and CLAW (Control of Lead at Work).

[61] Capodistria (today Koper in Slovenia), was part of the Venetian dominions up to 1797 and part of the Italian peninsula up to 1947.

[62] Traditionally, cabinet makers and makers of musical instruments used – and still use, Box-wood (*Buxus sempervirens*) for inlay and for small detailed components. Box-wood is a very dense, hard wood with excellent wear resistance. With these properties, Box-wood seemed the obvious choice of material for the tapered peg. Antique furniture and other artefacts from the period show that English hardwoods such as Oak, Ash (*Fraxinus excelsior*) and Elm were in use in Italy at the time although these would have been expensive imports. Hardwoods more often used by seventeenth-century Italian cabinet makers included European Lime Beech (*Fagus Sylvatica*) or Ash. Southern European Boxwood is likely to have been used to make smaller instruments or components of the Pulsilogia. Boxwood comes from a small shrub-like tree which when sawn, rarely produces billets of wood more than one metre long or 200mm in diameter.

[63] As seen in Section I, it shouldn't be forgotten that Antonio, Santorio's father, was a *bombardiere* in Capodistria for the Venetian Republic up to at least 1590 and so the young doctor must have had plenty of time to make himself familiar with any kind of artillery equipment.

[64] Also, heavier weights would put more strain on the instruments serving only to increase the rate of wear.

[65] As already stated, Santorio's decision to divide his scales into tens was largely arbitrary. As seen in Marci's example [Fig. 9], the scale presents 10x10 divisions, and the physician specifies that, the smaller are the divisions, the greater would be the precision of the instrument. This corroborates the hypothesis that seventeenth-century physicians using pulsilogia A1-2 would have used locally available measuring rods and measured the pulse each adopting his own scale divisions.

[66] See Section I.2, n. 16.

[67] *Arcana pulsuum:* might also be translated as "secrets of the pulse". Most likely, however, the term *arcanum* should be interpreted in the light of the Aristotelian theory of knowledge, whereby the process by means of which we grasp the universal notion of something is the most remote from, and the less clear to, our immediate perception. In this sense, then, *arcanum* stands not for 'obscure' or 'secret' but for "the most removed from the immediate perception," as indeed are the general notions and principles.

[68] A clear interpolation occurred after merging the two variants, as is often the case when Santorio presents his instruments. It is more than likely that all these quotes were extracted for the now lost book *On Medical Instruments*.

[69] From the Greek κοτύλη: 'bowl' or 'vase'.

[70] Santorio refers to his thermometers, which he called also *instrumenta temperamenti* and his followers preferably titled as *hydrolabia Sanctorii*.