



# The Collaboration between Anatomists and Mathematicians in the mid-Seventeenth Century with a Study of Images as Experiments and Galileo's Role in Steno's *Myology*

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## Abstract

Moving from Paris, Pisa, and Oxford to London, Amsterdam, and Cambridge, this essay documents extensive collaborations between anatomists and mathematicians. At a time when no standard way to acknowledge collaboration existed, it is remarkable that in all the cases I discuss anatomists expressed in print their debt to mathematicians. The cases I analyze document an extraordinarily fertile period in the history of anatomy and science and call into question historiographic divisions among historians of science and medicine. I focus on Steno's *Myology*, showing how his collaboration with mathematician Viviani led to a geometrical treatment of muscular contraction and to an epistemology inspired by Galileo. The collaboration between Steno and Viviani enables us to interpret a major text in the history of anatomy, one whose implications had so far eluded historians.

## Keywords

collaboration, anatomy, mathematics, mechanization, experiment.

## Introduction: Challenging Historiographic Boundaries

This essay addresses some historiographic matters intersecting the history of anatomy and of science in the seventeenth century:

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I wish to document and reflect on the collaboration between anatomists and mathematicians. Here I take the latter term quite broadly—as I believe is appropriate for the period—including scholars in geometry, astronomy, mechanics, and also physico-mathematics. In all the cases examined collaboration was acknowledged in print. In the seventeenth century there were no standard criteria for such public acknowledgements, which could be due to a variety of factors, such as academic seniority, intellectual allegiance, social standing, or personal friendship. They were in any case less common than one would expect from today's practices: this is one of the reasons why they are especially significant and worth examining. The scholars I discuss were identified as mathematicians in the acknowledgements or held chairs of mathematics at a university, or both. Following contemporary usage, I use the term anatomy quite broadly, including also what we call physiology.<sup>1</sup>

In a recent essay drawing on the classical tradition of Alexandre Koyré and Edwin Arthur Burtt, Peter Dear has defended a narrative of the Scientific Revolution based on the erosion of the boundaries between natural philosophy and mathematics. Dear was kind enough to acknowledge my query about anatomy, instantiated by Giovanni Alfonso Borelli's project to treat it as part of physics and mathematics much like astronomy, and to argue that "in principle" his own approach could be extended to the "life sciences." Indeed, since a good deal of what we now call the "life sciences" belonged to natural philosophy, the sharp separation between the history of science on the one hand and the history of medicine—especially anatomy—on the other has more to do with our own practices than with Early Modern ones. Even so, Dear's laudable suggestion has largely remained *lettera morta* among historians.<sup>2</sup>

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<sup>1</sup> Jerome J. Bylebyl, "Disputation and Description in the Renaissance Pulse Controversy," in Andrew Wear, Rober K. French, and Iain M. Lonie, eds., *The Medical Renaissance* (Cambridge, 1985), 223-245. Andrew Cunningham, "The Pen and the Sword: Recovering the Disciplinary Identity of Physiology and Anatomy before 1800," *Studies in History and Philosophy of Biological and Biomedical Sciences*, 33 (2002), 631-665; 34 (2003), 51-76.

<sup>2</sup> Peter Dear, "The Mathematical Principles of Natural Philosophy: Toward a Heuristic Narrative for the Scientific Revolution," *Configurations*, 6 (1998), 173-193, at 189-

Traditionally medicine and mathematics were linked because physicians relied on astrological data provided by mathematicians. In the seventeenth century, however, we witness the sharp decline of astrology and the rise of mechanistic ways of thinking. The mechanical and experimental philosophies became relevant to anatomists and anatomy became relevant to physico-mathematicians as a new frontier for their approach. Both sought to grasp the structure—or microstructure—and operation of the organs. This new alliance took many forms: in most cases the personal links among anatomists and mathematicians, and their working together—often elbow-to-elbow in the very same room—make it hard to reconstruct the details of those collaborations. The overall thrust of those links, however, points to their key role in shaping anatomical research and more broadly the intellectual life of the seventeenth century. In an account of his life relating to the prehistory of the Royal Society, the Savilian Professor of Mathematics at Oxford, John Wallis, reports meetings about 1645 in London among several scholars, including German émigré Theodore Haak, who first suggested them, divine John Wilkins, Samuel Foster, professor of astronomy at Gresham College, and physicians Jonathan Goddard, George Ent, Francis Glisson, and Christopher Merrett; they discussed the circulation of the blood, the chyliiferous and lymphatic vessels, Copernicanism, falling bodies, and optics. Later some moved to Oxford, where they were joined by the astronomer and mathematician Seth Ward, and physicians Ralph Bathurst, William Petty, and Thomas Willis. Wallis' report reveals that physicians and non-physicians alike, including mathematicians, discussed topics from different disciplines together. From Charles Webster to Harold Cook, several scholars have argued that physicians represented a sizable portion of the intellectual communities and scientific societies, such as the Royal Society. The papers by Karin Ekholm and Evan Ragland in this issue highlight the profound connections of anatomy with other areas, such as chymistry and the experimental philosophy more broadly. However, many sev-

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190. See also his *Discipline and Experience* (Chicago, 1995), and *Revolutionizing the Sciences: European Knowledge and its Ambitions* (Princeton, 2001). Giovanni Alfonso Borelli, *De motu animalium* (Rome, 1680-1), 2 vols; vol. 1, introduction.

enteenth-century historians of science still ignore medicine and anatomy. Take experiment, for example. Although anatomical experiments were a major feature of seventeenth-century research, the growing literature on experiment has focused largely on the physico-mathematical disciplines, sidelining anatomy. This one-sidedness is surprising both because seventeenth-century anatomical experimentation was widespread and remarkable in its own right, and because many anatomical experiments were performed in collaboration with other scholars, including mathematicians.<sup>3</sup>

This essay covers the third quarter of the century, thus excluding physicians who dealt directly with Descartes, such as Vopiscus Fortunatus Plemp, Henricus Regius, and Cornelis van Hoogelande, and late “Newtonian” physicians such as Archibald Pitcairne, George Cheyne, James Jurin, and Richard Mead, whose works have been amply documented. Of course, I do not aim at completeness but rather at reaching a critical mass showing that I am dealing not with isolated cases, but with a complex phenomenon worthy of investigation: the narrowly defined selection criteria highlight how widespread collaboration was. Although the theme of collaboration is central to Robert Frank’s *Harvey and the Oxford Physiologists*, here I argue that collaboration was wider than the Oxford group he studied and that it ranged from Paris and Pisa to Amsterdam and Cambridge and beyond. Some of the cases I examine are well known, others less so, but seen together they highlight the richness and creativity of anatomical research in the decades after Descartes’ death

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<sup>3</sup> Christoph J. Scriba, “The Autobiography of John Wallis,” *Notes and Records of the Royal Society*, 25 (1970), 17-46, at 39-40. Wallis was also present at Lower’s experiments on blood transfusion at Oxford in February 1665, Richard Lower, *Tractatus de corde* (London, 1669), 174. Charles Webster, *The Great Instauration: Science, Medicine, and Reform, 1626-1660* (London, 1975); Theodore M. Brown, *The Mechanical Philosophy and the “Animal Economy”* (New York, 1981); Robert J. Frank, *Harvey and the Oxford Physiologists* (Berkeley, 1980); Harold J. Cook, “The New Philosophy and Medicine in Seventeenth-Century England,” in David C. Lindberg and Robert S. Westman, eds., *Reappraisals of the Scientific Revolution* (Cambridge, 1990), 397-436; id., “Physicians and Natural History,” in Nicholas Jardine, James Secord, and Emma Spary, eds., *Cultures of Natural History* (Cambridge, 1996), 91-105. Recent literature on chemistry too points to the need for a new reflection on experimentation; see William R. Newman, *Atoms and Alchemy* (Chicago, 2006).

in 1650.<sup>4</sup> My first example involves the anatomist Jean Pecquet and mathematician Gilles Personne de Roberval in Paris around 1650. I shall also add some comments on Pecquet's parallel collaboration with Adrien Auzout. Examples two and three discuss scholars around the Cimento Academy, notably Marcello Malpighi, Lorenzo Bellini, and Borelli around 1660. Examples four and five are set in 1660s Oxford and London and involve the anatomists and physicians Thomas Willis and Richard Lower collaborating with Christopher Wren and Robert Hooke. With example six we move to the Netherlands, where the anatomist Jan Swammerdam collaborated with the mathematician and Burgomaster of Amsterdam Jan Hudde. Example seven involves the physician William Briggs and Isaac Newton. The centerpiece of this essay foregrounds the collaboration between Nicolaus Steno and Galileo's last disciple, Vincenzo Viviani in 1666-7: this example is particularly interesting because Steno relied on geometry in his study of muscles. Here my approach is especially rewarding for interpreting Steno's work and showing that he followed a methodology inspired by Galileo in which illustrations functioned as experiments. The significance of the cases I consider was already clear at that time, regardless of whether their specific findings were universally accepted, since they were all included in the *Bibliotheca anatomica*, an extensive collection of the main contributions to the field.<sup>5</sup>

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<sup>4</sup> On authorship and collaboration see D. Bertoloni Meli, "Authorship and Teamwork around the Cimento Academy," *Early Science and Medicine*, 6 (2001), 65-95. Vincent Aucante, *La philosophie médicale de Descartes* (Paris, 2006). Phillip R. Sloan, "Descartes, the Sceptics, and the Rejection of Vitalism in Seventeenth-Century Physiology," *Studies in History and Philosophy of Science*, 8 (1977), 1-28, at 20-28. Roger French, "Harvey in Holland: Circulation and the Calvinists," in Roger French and Andrew Wear, eds., *The Medical Revolution of the Seventeenth Century* (Cambridge, 1989), 46-86. Anita Guerrini, *Obesity and Depression in the Enlightenment* (Oklahoma, 2000); eadem, "Isaac Newton, George Cheyne and the *Principia Medicinæ*," in French and Wear, eds., *Medical Revolution*, 222-245; eadem, *Newtonian Matter Theory, Chemistry, and Medicine: 1690-1713* (Ph.D. Dissertation, Indiana University, 1983).

<sup>5</sup> Daniel Le Clerc and Jean Jacques Manget, eds., *Bibliotheca anatomica* (Geneva, 1685 and 1699), 2 vols.

## 1. Elasticity, the Thoracic Duct and the Arteries: Pecquet, Roberval, and Auzout

Robervallius, the most famous Reader of Mathematicks in Paris, in the King's Chair, did after this manner operate, while I was present, in favour at that vertue whereby the Air of it self doth dilate it self, indeed not without success.<sup>6</sup>

Jean Pecquet made his discovery of the receptacle of the chyle and thoracic duct public in the 1651 *Experimenta nova anatomica*, when he was still a student at the Paris medical faculty. Following Gasparo Aselli's discovery of the milky veins, carrying chyle away from the intestine, Pecquet set out to investigate their path more thoroughly. Aselli had dissected a dog after it had eaten, when the milky veins were turgid with chyle and especially visible; his discovery was an accidental event, one he marked by the exclamation "eureka!" Following traditional anatomical views, Aselli believed that milky veins carried chyle to the liver for the purpose of sanguification; he followed up his initial finding with a series of observations on several animals. Pecquet's findings too stemmed from an accidental discovery whereby he saw a white fluid in the vena cava of a dog; initially he thought it was pus but upon reflection on the health of the dog he changed his mind and sought its origin starting a systematic project over three years involving the dissection and vivisection of over one hundred animals. His results were remarkable: Pecquet was able to show that Aselli's milky veins did not lead to the liver, but rather coalesced into a receptacle located between the kidneys, near the aorta, leading all the way in a ladder-like structure, parallel to the backbone, to the subclavian vein, in the vicinity of the heart. Traditionally vivisection was used to investigate the actions or motion of the parts, as Harvey had done in *De motu cordis*; both Aselli and Pecquet, however, relied on vivisection for the investigation of structures that were so fragile and ephemeral as to become rapidly invisible in the dead animal. In the engraving accompanying his publication (see Figure 1), Pecquet showed the dissected dog on the right, while

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<sup>6</sup> Jean Pecquet, *Experimenta nova anatomica* (1651; I shall use the expanded 1654 edition), 51. I have slightly modernized the English translation, *New Anatomical Experiments* (London, 1653), 92.

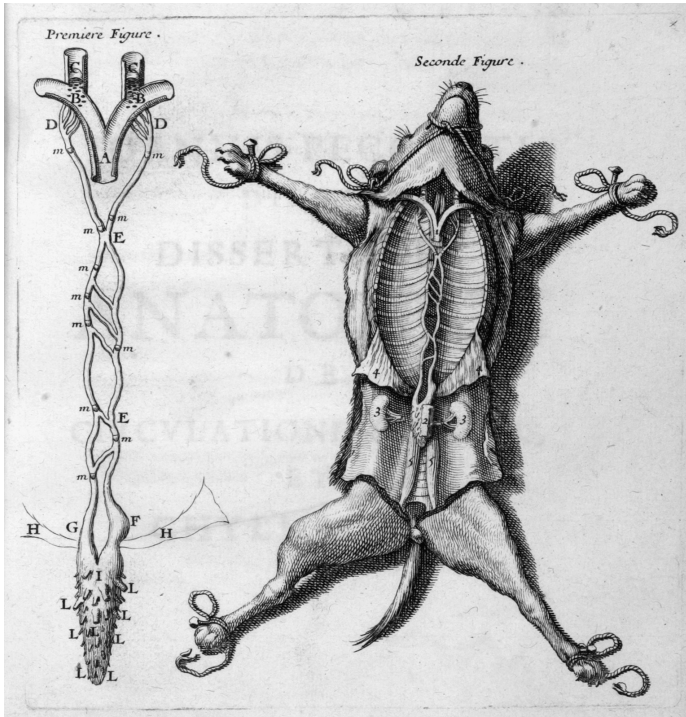


Figure 1. Pecquet, *Experimenta nova anatomica*: thoracic duct.

on the left he drew for clarity's sake the receptacle of the chyle and the thoracic duct on their own. His finding resulted in an anatomical earthquake that left the largest organ in the body deprived of its role: far from making blood from chyle, the liver received no chyle at all and was therefore deprived of its primary purpose.<sup>7</sup>

Significant as Pecquet's findings were, the matter did not end with structure alone. Pecquet sought to provide a mechanistic account of the motion of chyle from the intestine and towards the subclavian vein without having recourse to attraction; this was especially significant for humans, given that chyle had to move upward because of our posture. He included a section titled "Experimenta physico-

<sup>7</sup> Gasparo Aselli, *De lactibus sive lacteis venis* (Milan, 1627; facsimile edition by Pietro Franceschini, Milan, 1972), 20. Pecquet, *Experimenta*, chapters 1-2.

mathematica de vacuo,” in which he presented an impressive series of experiments on the Torricellian tube that had been performed in recent years by Roberval, Blaise Pascal, and Pecquet’s friend Auzout.<sup>8</sup> His aim was to show that besides weight, air has the property to expand once it is compressed. Pecquet called this property “elater” or “elasticity,” “ressort” in French, and compared it to the tendency of wool or sponges, or also a bow or a pneumatic gun, to regain their original state once compressed by a weight or another means. In his objections to Descartes’ *Meditationes*, Marin Mersenne had used the term “elater” in this sense, meaning a mechanical device.<sup>9</sup> Pecquet too used the term “elater” in this same sense and applied it to describe the properties of air. He rejected attraction by relying only on mechanical notions such as elasticity and pressure due to respiration in order to explain the motion of chyle, but he also talked of the innate “elater” of blood vessels aiding the circulation of the blood; thus he implicitly questioned Harvey’s claim in the introduction to *De motu cordis* that the arteries are filled like leather bottles rather than dilating like bellows. According to Pecquet, both the power of the blood pushed by the heart and the elasticity of

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<sup>8</sup> Pecquet, *Experimenta*, 50, states that the experiments had not been previously published, “nondum typis concessa.” However, Pascal’s experiment had been published in a rare pamphlet in 1648, *Récit de la grande expérience de l’équilibre des liqueurs* (Paris, 1648). See the texts and introductory material collected by Léon Brunschvicg in Pascal, *Oeuvres* (Paris, 1908), vols 1-2. Daniel C. Fouke, “Pascal’s Physics,” in Nicholas Hammond, ed., *The Cambridge Companion to Pascal*, (Cambridge, 2003), 75-101. Experiments on the void included also the physician Pierre Guiffart, who wrote a *Discours du vide* (Rouen, 1647) and in 1652 *Cor vindicatum* (Rouen, 1652), in which he discussed Pecquet’s findings. Pecquet, Roberval, and Auzout were among the founding members of the *Académie Royale des Sciences*, thus their association continued well beyond the period covered here.

<sup>9</sup> René Descartes, *Oeuvres*, ed. by Charles Adam and Paul Tannery (Paris, 1897-1913), 12 vols, vol. 7, 414: “beneficio elateriorum mechanicorum.” Pecquet, *Experimenta*, 26-27: “Elaterem hic seu virtutem elasticam voco innatam compressae seu coactae rei ad naturalem statum nitentis propensionem; hac lana vel spongia gravanti pondere liberatae ad pristinam redeunt extensionem, hac arcus sagittam impellit, hac condensatus in sclopo pneumatico aer dato exitu plumbum tanta violentia / erudit quanta pulvis tormentarius solet expellere. Elaterem etiam appello rei plus juxto extensae ad naturalem mediocritatem reditum, sic vescica immisso aere turgidior (dato exitu aeri) sese ipsam contrahit; uno verbo mihi Elater sonat, quod vulgo nostro *un ressort*.”



the arteries contribute to the blood-flow. He further illustrated his claim about the role of pressure and elasticity on the motion of chyle from the intestine by means of the example of children squeezing a water-filled bladder in which they have made tiny holes with a needle, thus causing the water to squirt in many directions.<sup>10</sup>

Among the experiments reported by Pecquet, I wish to focus on Roberval's and Auzout's, both for their importance to Pecquet and because of his closeness to the two mathematicians, whereas his account of Pascal's celebrated Puy-de-Dôme experiment was second-hand. Roberval was the leading mathematician in Paris, where he held the Ramus chair of mathematics at the Collège Royale; moreover, he had been a very active member in Mersenne's circle, contributing reflections and experiments on a wide range of topics, from the motion of projectiles to barometric experiments. At an experimental demonstration in front of several savants, including Pecquet, he used the air bladder of a carp, emptied it, tied the aperture, and inserted it in a Torricellian tube. When the tube was turned upside down and the mercury descended, the carp bladder expanded in the space at the top (see Figure 2). Roberval attributed this phenomenon to the property of air to dilate itself once compressed. Besides Pecquet's testimony that he witnessed Roberval's experiment, it is especially significant to point to a personal link between them through Pecquet's surviving dedicatory copy to Roberval of the expanded 1654 edition of *Experimenta nova anatomica* (see Figure 3). This copy may suggest not only an association between Pecquet and Roberval, but also a form of tacit assent on Roberval's part to the publication of his experiment by Pecquet.<sup>11</sup>

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<sup>10</sup> Pecquet, *Experimenta*, 74, 82. William Harvey, *De motu cordis* (Frankfurt, 1628), English translation by K.J. Franklin (London, 1963, revised edition 1990), *The Circulation of the Blood*, 10-11 and 112-114. Roger French, *William Harvey's Natural Philosophy* (Cambridge, 1994), 364-70. Galen too in *On the natural faculties*, I.7 referred to children playing with bladders filled with air with rather opposite intents, in order to show that growth can only be accomplished by nature rather than mechanically or by art.

<sup>11</sup> Pecquet, *Experimenta*, 51-5. Pascal, *Oeuvres*, 2:53-76, "Expériences nouvelles touchant le vuide." William R. Shea, *Designing Experiments and Games of Chance* (Canton, MA, 2003), 88-97.

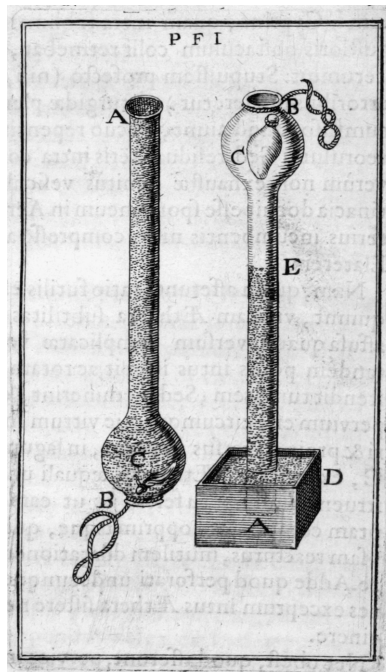


Figure 2. Pecquet, *Experimenta nova anatomica*: Roberval's carp bladder experiment.

Auzout was a mathematician and astronomer best remembered for his work on the movable-wire micrometer. Pecquet called him as a witness to his investigations and called him “a man endowed with all sorts of Learning, by whose help, advice, and intimate friendship, not a few things were discovered to me.” Auzout contributed to *Experimenta nova anatomica* an “epistola gratulatoria” to the author, “amico suo singulari.” His experiment involved an ingenious contraction whereby he inserted a Torricellian tube inside another—the so-called vacuum in the vacuum experiment (See Figure 4). The Torricellian tube FC inside the larger one EA is sealed by a pig's bladder: whilst mercury in EA descends to twenty-seven inches, that in FC goes all the way down. By piercing the bladder, air enters the space above E and the mercury in the large tube descends from E, whilst that in FC ascends: when the mercury in the large tube has descended completely, that in the small tube reaches twenty-seven inches. Pecquet saw this experiment too as

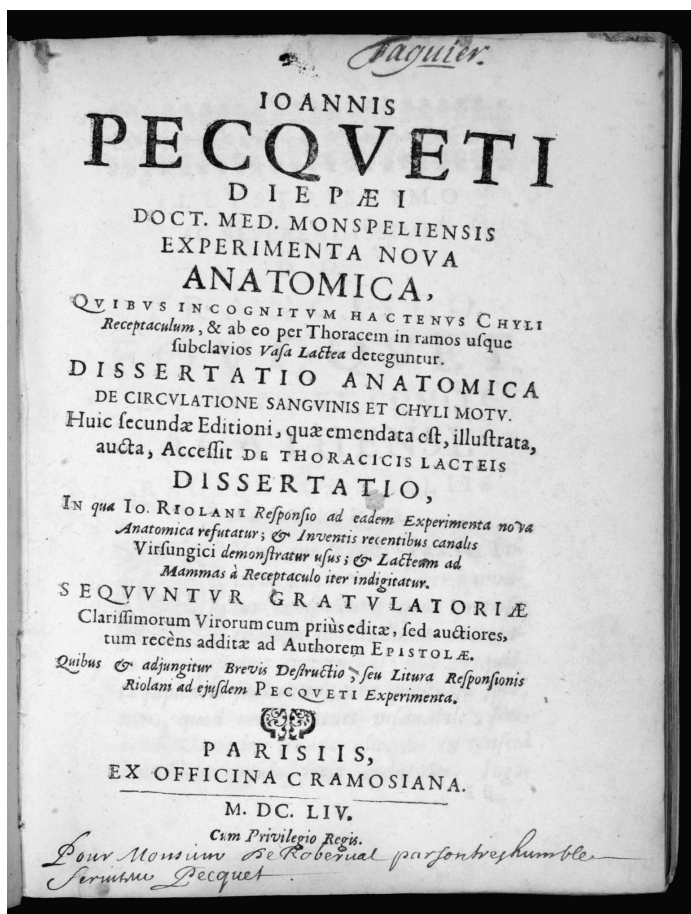


Figure 3. Pecquet's dedication copy to Roberval of the 1654 *Experimenta nova anatomica*.

confirming his views about the elater of the air, which was able to expand once it had been compressed, like a sponge or wool.<sup>12</sup>

Thus Pecquet's book involved anatomy and the physico-mathematical sciences, providing an analysis that incorporated the results of recent findings and debates on the Torricellian experiment. His

<sup>12</sup> Pecquet, *Experimenta*, 19, 155-163; I have slightly modernized the English translation, *New Anatomical Experiments* (London, 1653), 36-37. The "Epistola gratulatoria" was also included in the first edition. Shea, *Designing Experiments*, 99-105.

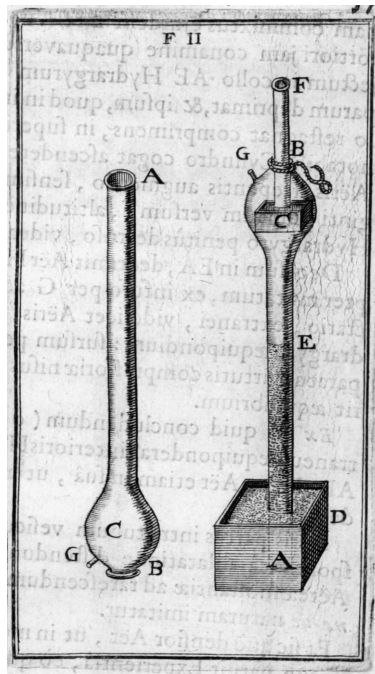


Figure 4. Pecquet, *Experimenta nova anatomica*: Auzout's vacuum in the vacuum experiment.

treatise was one of the most effective tools for spreading mechanistic anatomy, since it went through several editions and its findings were widely debated. Although Descartes had already introduced key elements of his mechanical understanding of the body well before the posthumous appearance of *De homine* in 1662, starting from the 1637 *Discours de la Méthode*, his knowledge of anatomy was sketchy. By contrast, Pecquet was able to join a major anatomical finding with a mechanical understanding relying on the most recent experiments on air and its properties due to his connections with Roberval and Auzout. Thus his *Experimenta* is a major work three times over: as an anatomical treatise, as a contribution to research on the vacuum and on properties of air, and as a bridge between anatomy and the physico-mathematical disciplines. Often anatomists simply borrowed findings and notions from other areas, but Pecquet not only reported and used a number of experiments

with the Torricellian tube, but also developed the notion of “elater” or elasticity of the air in a fruitful fashion. It is through the English translation of Pecquet’s *Experimenta* that terms like “elater,” often rendered as “spring” and “elastick,” entered the English language. His work—whole or in part—was reprinted seven more times before 1661, including a Genoa edition in 1654 that in all probability reached Florence in the same year: this volume bears a dedication by the publisher to the mathematician Giovanni Battista Baliani. In 1656 Viviani appeared to be interested in Pecquet’s *Experimenta* because of the vacuum experiments and requested a copy from the Paris lawyer Elia Diodati. As a result, the members of the Cimento Academy became familiar with many experiments on the void through Pecquet’s work, and repeated many of them in the *Saggi di naturali esperienze*.<sup>13</sup>

## 2. Microscopy and the Lungs: Malpighi and Borelli

As to the purpose for which all these things occur, besides that which I have espoused in the first letter on the pulmonary mixing, you seem to have fully lit upon, nor should your mind be defrauded of this most famous discovery of yours, which you kindly communicated to me by letter, in which you subtly philosophize observing the marvelous portents of nature in plants.<sup>14</sup>

<sup>13</sup> W.E. Knowles Middleton, *The Experimenters. A Study of the Accademia del Cimento* (Baltimore, 1971), 110, 116, 129. Joannes A. Munierus, *De venis tam lacteis thoracis quam lymphaticis* (Genoa, 1654), 31, states that the physico-mathematical experiments have been omitted because they were deemed irrelevant, thus highlighting the novelty of Pecquet’s approach. Pecquet’s work, in one of its editions, was known in Florence by 1657: Middleton, *Experimenters*, 110n. Paolo Galluzzi and Maurizio Torrini, eds., *Opere dei discepoli di Galileo Galilei* (Florence, 1975-), 2:122, Giovanni Battista Baliani to Famiano Michelini, Genoa, 17 January 1654; at 349-355, Elia Diodati to Vincenzo Viviani, Paris, 24 June 1656, at 354; Diodati stated that the book was available at the cost of three lire.

<sup>14</sup> Marcello Malpighi, *Epistolae de pulmonibus* (Bologna, 1661), in Malpighi, *Opera omnia*, 2 vols. (London, 1687), 2:143: “in quem vero finem haec omnia fiant, ultra ea quae superiori epistola tetigi de pulmonaria miscella, tu ipse visus es apprimè deprehendisse, nec celeberrimo tuo hoc invento mens est fraudanda, quod humanitate tua ad me exaratis literis commisisti, quibus subtiliter philosophabar mira in vegetabilibus portenta naturae observando.” D. Bertoloni Meli, “The New Anatomy of Marcel-

In 1661 Malpighi, then professor of practical medicine at Bologna, published two *Epistolae* on the lungs, both dedicated to Borelli, “Most renowned Professor of Mathematics at Pisa University.” The opening quotation is taken from the second *Epistola*, in which Malpighi reported what Borelli had communicated to him in a private letter. It would be highly reductive, however, to limit Borelli’s role to that of interpreter of Malpighi’s findings. Between 1656 and 1659 Malpighi had been Borelli’s colleague at Pisa, and during that time they had developed a profound friendship and intellectual bond. In his posthumous *Vita* Malpighi acknowledged that he arrived at Pisa as an Aristotelian and was instructed in the free Democritean philosophy by Borelli.<sup>15</sup>

Borelli had been a student of Galileo’s disciple Benedetto Castelli. As the holder of Galileo’s former chair of mathematics at Pisa and prominent member of the Cimento Academy, Borelli was the leading scholar of the Galilean school. He had long planned to write a book on the motion of animals; his *De motu animalium* appeared posthumously in 1680-1, but was preceded by *De vi percussionis* (1667) and *De motionibus naturalibus a gravitate pendentibus* (1670), two works in the physico-mathematical disciplines that he presented as leading to his anatomy. Throughout his life Borelli had sought the help and knowledge of anatomists: during his three years at Pisa Malpighi put his dissection skills at Borelli’s disposal, while the latter, besides providing philosophical mentoring, alerted Malpighi to the potential of the microscope as a tool for anatomical investigation.<sup>16</sup>

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lo Malpighi,” in D. Bertoloni Meli, ed., *Marcello Malpighi, Anatomist and Physician* (Florence, 1997, hereafter: *MAP*), 21-62, at 35-39.

<sup>15</sup> Malpighi, *Opera omnia*, 2:133, 140. Susana López Gómez, “Marcello Malpighi and Atomism,” in *MAP*, 175-189, at 175.

<sup>16</sup> Marcello Malpighi, *Correspondence*, ed. by Howard B. Adelman, 5 vols, (Ithaca, 1975, hereafter *MCA*), 1:87-88, 13 May 1661, Borelli wrote to Malpighi that he had a microscope by the leading maker Eustachio Divini. A few years later he advised Malpighi that Jacopo Ruffo at Messina had several lenses and that by mounting two in a tube at the appropriate distance, which could be easily found by trial and error, one could fabricate microscopes of different sizes; *MCA*, 1:159-160, Borelli to Malpighi, Pisa, 12 April 1663. Presumably Borelli was acquainted with microscopy from his time at Messina before 1656.

Upon his return to Bologna, Malpighi continued to pursue anatomical researches and to discuss them with Borelli, now no longer in person but through correspondence. As a result of his devotion to Borelli, Malpighi addressed his first publications to him. Malpighi's *Epistolae* are quite brief and contain the report of anatomical observations with the help of the microscope and of other techniques of investigation, including drying the lungs and injecting them with liquids such as water or mercury. His techniques were so sophisticated that even Borelli, who was receiving detailed instructions and had excellent microscopes, probably better than Malpighi's, had difficulties in reproducing the observations. In his investigation, Malpighi revealed his mastery in microscopy from his very first publication, relying on complex preparations and observations under increasing magnification under direct and reflected light.<sup>17</sup>

Traditionally, the lungs were considered to be a fleshy organ, somewhat lighter in weight than others, but their inner structure, as the inner structure of all other organs, was unknown. Anatomists noticed that the lungs were lighter in color than other viscera, such as the liver or kidneys. According to many, the purpose of the lungs was to provide fresh air in order to cool the excessive heat of the heart. This doctrine of the heart's heat was still prevalent in the seventeenth century and was accepted by Descartes, for example. At Pisa, however, such views were received with skepticism. In order to disprove them Borelli performed a stunning vivisection experiment: He inserted a thermometer in the viscera of a stag, showing that the temperature was not higher in the heart than elsewhere.<sup>18</sup>

In his *Epistolae* Malpighi showed that the substance of the lungs was not fleshy or spongy but consisted of communicating *alveoli* or small cavities separated by thin membranes. His illustrations are the first images of the microstructure of an organ ever printed: Figure 5 shows different arrangements of air sacs (III), with the opening of the trachea at the bottom, and portions of the lungs

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<sup>17</sup> *MCA*, 1:87 (13 May 1661) and 177 (17 August 1663). Marcello Malpighi, *Opere scelte*, ed. by Luigi Belloni (Turin, 1967), 95 and 97.

<sup>18</sup> Borelli, *De motu animalium*, part II, prop. 96.

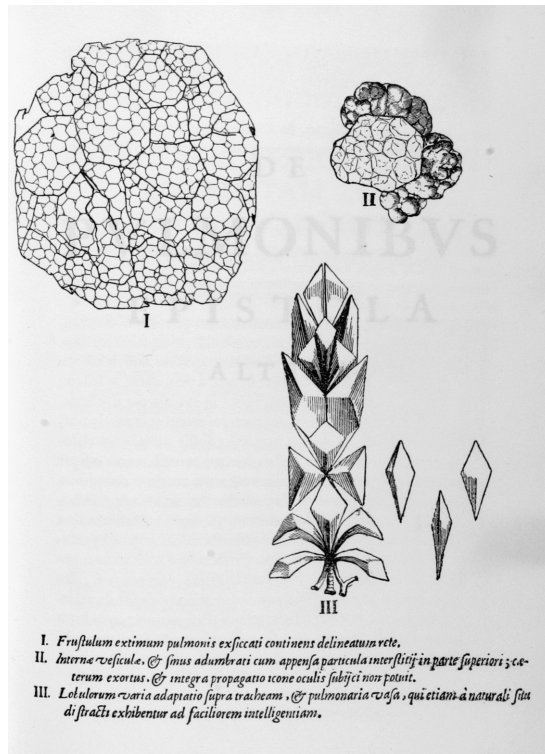


Figure 5. Malpighi, *Epistolae de pulmonibus*: microstructure of the lungs.

under magnification (I and II). It was Borelli who had urged Malpighi to follow Descartes in including figures, arguing that they were powerful convincing tool and Descartes had deceived many in this way.<sup>19</sup>

In the second *Epistola*, by observing the lungs of frogs and tortoises, whose microstructure is easier to detect than those of higher animals, Malpighi was able to argue that the network visible on the lungs' membranes consisted of blood vessels; he also observed the contrary motion of blood in arteries and veins, thus offering a visual display of the circulation of the blood, and detected their junctions, showing that blood flows always inside vessels. Thus air seemed

<sup>19</sup> *MCA*, 1:54-56, 4 January 1661, on 55, Borelli to Malpighi.



never to be in direct contact with blood. As a result of his structural findings, Malpighi suggested that the lungs serve to mix blood with the help of air pressure and with their motion, and sought to confirm this purely mechanical interpretation with a number of anatomical observations as well as remarks on human activities; for example, he mentioned women who beat fresh blood with their hands or with a stick in order to prevent the separation of its components, or who mix flour with water, as well as the network of blood vessels in the incubated egg, and the gills of fishes. In addition, Malpighi clarified his views on the basis of a peculiar suggestion put forward by Borelli in a form that today would probably involve multiple authorship. This example is representative of a form of collaboration whereby the anatomist described the structure and Borelli explained the operation and purpose. Recalling having seen in Rome vine and jasmine grafted onto a lemon trunk, Borelli thought that the arrangement of vine and jasmine vessels transforms the acid juice of the lemon into a sweet one. Analogously, the lungs would rearrange the particles of blood mixed with chyle and make them ready to form all the body parts. Borelli's opinion relied both on Pecquet's recent findings and on a corpuscular view of matter whereby its properties depend on the arrangements of its constituent parts. In line with Borelli's views about color—which he deemed an unimportant property—Malpighi said not a word on the color change of blood.<sup>20</sup>

Despite the break between Malpighi and Borelli towards the end of 1667, the initial stimulus and research framework provided by Borelli did not disappear: in all his subsequent publications, including his *Opera posthuma*, Malpighi continued to use the microscope searching for the constituents of the organs and their arrangements as a key to understanding animals and plants in a mechanistic fashion.<sup>21</sup>

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<sup>20</sup> D. Bertoloni Meli, "New Anatomy," 35-36; "Authorship and Teamwork," 76-78.

<sup>21</sup> On Malpighi's *Opera posthuma* see my "The Posthumous Dispute between Borelli and Malpighi," *MAP*, 245-273.

### 3. Microscopy and the Kidneys: Bellini and Borelli

It pleases me here only to report that which the previously praised Borelli deduces about the separation of the serum from the structure of the kidneys here discovered.<sup>22</sup>

In 1662 Lorenzo Bellini, then still a student of nineteen, published a treatise on the kidneys, *Exercitatio anatomica de structura et usu renum*. Following Malpighi's departure from Pisa in 1659, Borelli groomed the young Bellini, who gained international reputation with this work and eventually was to gain the chair of anatomy at Pisa. Although Bellini was at Pisa working with Borelli and Malpighi was at Bologna, the two cases show remarkable similarities. Both anatomists found it hard to determine the purposes of the structures they had uncovered and relied on Borelli for elucidations; reciprocally, Borelli relied on their skills in dissection and with the microscope to uncover the structure of an organ. Bellini and Borelli probably followed Malpighi's precedent in publishing a work in which each contributed a section.

Bellini argued that the structure of the kidneys consists not in a parenchyma similar to the heart or liver, as claimed by some, but in a series of fibers and vessels. These are not muscular, since by boiling them they become smaller, whereas muscles increase in volume. The external surface of the kidneys is covered by a large number of *sinuli* or tiny folding vessels where the secretion of urine occurs. These *sinuli* are best seen by a combination of injection of ink into the blood vessels and microscopy. Bellini thought he had identified Y-shaped structures as the sites where the separation of urine occurs: arterial blood separates into urine and venous blood.<sup>23</sup> Having described the structure of the kidneys, Bellini left to Borelli the explanation of their mode of operation and purpose.

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<sup>22</sup> Lorenzo Bellini, *Exercitatio anatomica de structura et usu renum* (Florence, 1662). Felice Grondona, "L'esercitazione anatomica di Lorenzo Bellini sulla struttura e funzione dei reni," *Physis*, 5 (1963), 423-463, at 455: "Solum hic referre libet, quid superius laudatus Borellus ex hac inventa Renum constitutione ad serum separandum deducat."

<sup>23</sup> Bellini, *Exercitatio*, at 447-451. For Bellini's figure see Bertoloni Meli, "Posthumous Dispute," 254.

Borelli argued that secretion occurs not by attraction, familiarity, or sympathy, but solely as a result of the vessels' configurations. His account relied on some experiments on capillarity that were being discussed at the Accademia del Cimento—an example of the interaction between the experiments of the Medicean academy and anatomical research. Moreover, Borelli drew analogies with fluids percolating through solid bodies and membranes; for example, mercury penetrates the pores of gold, though air and water do not; some membranes or skins are permeable to water, though not to air. In a similar fashion, arterial blood divides into urine going through the renal small siphons, whereas venous blood goes through the veins. Borelli believed that this process was helped by respiration, since the compression of the abdomen during inspiration would make urine exude from its tubes. In this he was following Pecquet, who had argued that chyle moves in the milky veins as a result of the compression of the abdomen due to respiration.<sup>24</sup>

Bellini's and Borelli's choice to contribute different portions of a text authored by Bellini was probably seen as peculiar already in the seventeenth century, since in the 1664 edition the text was partitioned in two and each part was attributed to a separate author, Bellini for *De structura renum observatio anatomica*, and Borelli for *De illorum usu iudicium*.<sup>25</sup> The cooperation between Bellini and Borelli, however, went beyond the division of authorial responsibilities. As in Malpighi's case, Borelli inspired Bellini to understand anatomy in mechanistic terms and to employ the microscope in order to bridge the gap between the mechanistic program and anatomical investigations. In 1666 Malpighi showed that Bellini's *sinuli* were merely excretory vessels, not the locus of separation between arterial blood and urine as elaborated by Borelli. Malpighi went on to locate that locus in some globular structures made visible by ink injections. Despite their disagreements, however, Malpighi's work was carried out very much in the same spirit, as was Bellini's fur-

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<sup>24</sup> Bellini, *Exercitatio*, in Grondona, "L'esercitazione," 455-462. On capillarity see López Gómez, "Marcello Malpighi," 179-180.

<sup>25</sup> The edition appeared in Strasburg, "Apud Simonem Paulli," 1664. Bertoloni Meli, "Authorship and Teamwork," 78-81.

ther research. In 1683, four years after Borelli's death, he published *De urinibus et pulsibus*, a book in which medicine was "handled with mathematics, and with the mechanics" in such a way that even Malpighi found it too taxing.<sup>26</sup>

#### 4. Injections and the Iconography of the Brain: Willis and Wren

Besides the helps brought me by his [i.e., Richard Lower, physician and anatomist] most skilful dissecting hand, it becomes me not to hide, how much besides I did receive from these most famous Men, Dr. Thomas Millington, Doctor of Physick, and Dr. Chr. Wren Dr. of Laws, and Savill Professor of Astronomy; both which were wont frequently to be present at our Dissections, and to confer and reason about the uses of the Parts. ... But the other most renowned Man, Dr. Wren, was pleased out of his singular humanity, wherewith he abounds, to delineate with his own most skilful hands, many figures of the Brain and Skull, whereby the work might be more exact.<sup>27</sup>

In 1664 Thomas Willis published a major treatise on the brain, *Cerebri anatome*. Willis was one of the leading anatomists and physicians in England who became Sedleian Professor of Natural Philosophy at Oxford following the Restoration. The opening quotation from the preface to the reader shows that this work resulted from the collaboration among several scholars. As Robert Frank has argued in his important work on respiration, collaboration was a standard mode of operation at Oxford. The contents of Willis's *De cerebro* are too extensive to be treated here in any detail; therefore I discuss some aspects at the center of the collaboration with Wren, namely the discussion on the uses and drawing of the figures, as mentioned in the opening quotation, and the role of injections. In 1661 Wren had moved from Professor of Astronomy at Gresham College to the Savilian chair of Astronomy at Oxford. Besides his celebrated work as an architect and his wide-ranging activities in the mathematical disciplines, Wren had related interests in chemis-

<sup>26</sup> Malpighi, *Opere scelte*, 158. *MCA*, 2:892-893, Malpighi to Ferrarini, Bologna, 27 February 1683. Malpighi had seen the book through the press and is mentioned as a revisor for censorship.

<sup>27</sup> Thomas Willis, *Cerebri anatome* (London, 1664), English translation by Samuel Portage *The Anatomy of the Brain* (London, 1681), preface to the reader.

try and anatomy, especially muscular motion, and was also able to dissect.<sup>28</sup>

Willis's acknowledgement refers to Wren's presence at dissections and discussions about "the uses of the Parts"; as we have seen above, this was also Borelli's role in his collaboration with anatomists. Borelli, however, was quite dismissive of this portion of Willis's work, and in a letter to Malpighi he argued that little could be learned from the structure of the brain about imagination and fantasy. Willis discussed these topics arguing that

the Imagination is a certain ondulation or wavering of the animal Spirits, begun more inwardly in the middle of the Brain, and expanded or stretched out from thence on every side towards its circumference: on the contrary, the act of the Memory consists in the regurgitation or flowing back of the Spirits from the exterior compass of the Brain towards its middle.

As to fantasy, he stated that "sometimes a certain sensible impression, being carried beyond the callous Body, and striking against the *Cortex* of the Brain it self, raises up other species lying hid there, and so induces Memory with Phantasie."<sup>29</sup>

Wren, however, made available also his drawing skills, something that was unusual from a mathematician though not surprising in his case, given his architectural background. In addition, Wren's anatomical work included injections, and this is an area relevant to a crucial aspect of Willis's investigations on the brain and to the drawings in *De cerebro*. The most celebrated finding in *Cerebri anatome* is that the arteries form a loop at the base of the brain, later known as the "circle of Willis." The illustration was probably drawn by Wren (see Figure 6) and shows, in the middle, the dark loop of arteries at the base of a human brain. Willis showed that the col-

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<sup>28</sup>) William C. Gibson, "The Bio-Medical Pursuits of Christopher Wren," *Medical History*, 14 (1970), 331-341. James A. Bennett, "A Note on Theories of Respiration and Muscular Action in England c. 1660 (Christopher Wren)," *Medical History*, 20 (1976), 59-69. Frank, *Harvey and the Oxford Physiologists*, chapter 3 and *passim*. Lisa Jardine, *On a Grand Scale: The Outstanding Career of Sir Christopher Wren* (New York, 2002).

<sup>29</sup>) *MCA*, 1:236, Borelli to Malpighi, 6 October 1664. Willis, *Anatomy of the Brain*, 91 and 96.

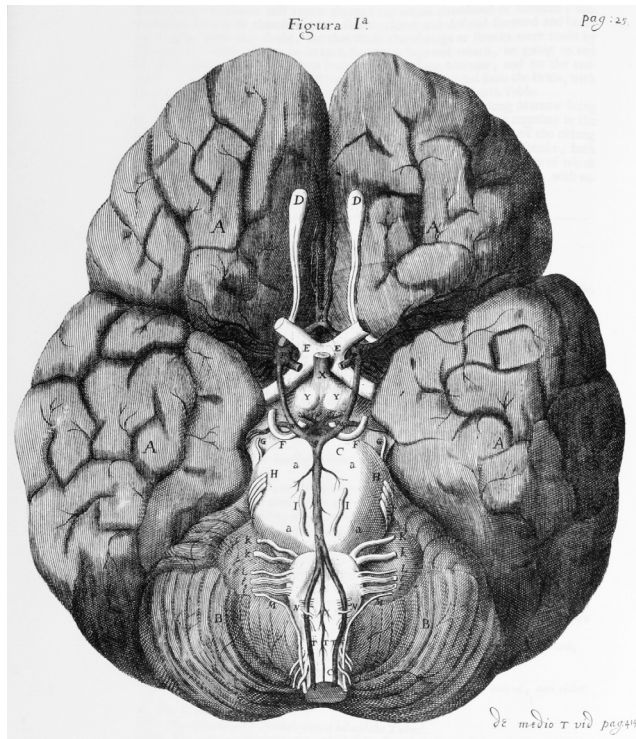


Figure 6. Willis, *Cerebri anatome*: the circle of Willis illustrated by Wren.

ored liquid injected into an artery on one side is soon seen to descend from the artery on the other side: thus the anastomoses among the arteries regulate blood flow to the brain, preventing it to be deprived of, or engorged with, blood: injections in this case were used not so much to reveal a structure as to investigate its mode of operation and purpose. Willis was able to confirm the purpose of the arterial loop he had detected in a notable postmortem dissection, where he found the right carotid artery bony and almost entirely obstructed, yet the man lived a normal life because of the abnormal enlargement of the compensating vertebral artery of the same side: here a concealed diseased state shed light on the normal purpose of the arterial anastomoses.<sup>30</sup>

<sup>30</sup> Willis, *Anatomy of the Brain*, 72-3 and 82-83. Francis J. Cole, "The History of

## 5. The Mechanics and Chemistry of Respiration: Lower and Hooke

I acknowledge my indebtedness to the very famous Master *Robert Hooke* for this experiment—by which the lungs are kept continuously dilated for a long time without meanwhile endangering the animal's life—and the opportunity thereby given to me to perform this piece of work.<sup>31</sup>

In the mid-1660s the Royal Society was the theater of a remarkable series of investigations carried out primarily by Lower and Hooke. Lower was an anatomist and physician active in the circle of Willis at Oxford: he took his medical degree at Oxford in 1665 and was elected fellow at the Royal Society in 1667. Hooke worked as Boyle's assistant in Oxford in the 1650s; in 1663 he became a fellow of the Royal Society, where he was also curator of experiments, and in 1664 professor of geometry at Gresham College. While Robert Frank has reconstructed their collaboration in remarkable detail, it is useful to reconsider it here from a broader perspective.<sup>32</sup>

In October and November 1664 the Royal Society debated whereas air enters the body through the lungs. The fact that during the vivisection of a dog it was possible to revive the heartbeat by blowing air into Pecquet's *receptaculum chyli*, whence it reached the heart through the thoracic duct, suggested a role for air in heart pulsation. In November Hooke, Goddard, and Oldenburg inserted a pair of bellows into the trachea of a dog and inflated its lungs. Hooke opened the thorax and cut the diaphragm, observing the heart beating regularly for over one hour as long as air was in the lungs. He could not determine whether air entered the lungs, but he estab-

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Anatomical Injections," in Charles Singer, ed., *Studies in the History and Method of Science* (Oxford, 1917-21), 2:285-343, at 292.

<sup>31</sup> Richard Lower, *Tractatus de corde* (London, 1669), 167-8, translation by Kenneth J. Franklin in Robert T. Gunther, ed., *Early Science in Oxford*, vol. 9 (Oxford, 1932).

<sup>32</sup> Allan Chapman, *England's Leonardo. Robert Hooke and the Seventeenth-Century Scientific Revolution* (Bristol and Philadelphia, 2005), especially chapters 2 and 6. Frank, *Harvey*, chapter 3 and *passim*.

lished that the motion of the heart was related to the inflation of the lungs, even though the two were not synchronous.<sup>33</sup>

Crucially, the English investigators asked questions about the color of blood that Malpighi and Borelli had ignored. Lower, following Willis, attached great importance to the fermentation of blood and color change. In the *Vindicatio* (London, 1665) he believed that blood changes color in the heart as a result of a ferment in the left ventricle; he also believed that blood in the lungs was venous, probably because in his early trials the animal's lungs had collapsed and were empty of air. But additional experiments refuted his initial view. On 10 October 1667 Hooke and Lower performed an experiment at the Royal Society analogous to that of 1664, but this time they relied on two pairs of bellows instead of one, producing a continuous air flow. An incision in the pleura allowed air to exit the lungs, which remained inflated. Thus the animal was kept alive without motion in the lungs, showing that their motion was not indispensable to life.<sup>34</sup>

Lastly, Hooke and Lower performed yet another experiment in two parts on a dog. First, in the initial vivisection, they closed the trachea and showed that the blood coming from the cervical artery, after the blood had gone through the left ventricle of the heart, was venous. Thus the change of color of the blood did not occur in the heart. Then the animal died, and they performed the insufflation experiment we have seen above with the two pairs of bellows, managing to obtain arterial blood from the pulmonary vein. Thus it was not the motion of the lungs, or a ferment in the heart, or the animal's heat that was responsible for the change of color of blood, but only air.<sup>35</sup> This experiment strikes me as especially significant in showing that the change of color and properties of blood was not due to the soul or one of its faculties, because the animal

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<sup>33</sup> Frank, *Harvey*, 157-160, 329n79. In the introduction to *De motu cordis* Harvey reported that Galen too had performed similar experiments: Harvey, *The Circulation*, 13.

<sup>34</sup> Lower, *Vindicatio*, 117-118. *Philosophical Transactions*, 2 (1667), 509-516. Frank, *Harvey*, ch. 7, especially 188-192.

<sup>35</sup> Lower, *De corde*, 165-167. Frank, *Harvey*, 208-217.



was dead: in this respect it can be seen as a hallmark of the mechanical philosophy applied to anatomy.

Experiments and debates on respiration occupied the English virtuosi for several years and involved instruments and techniques ranging from the air pump to chemical analysis. Yet I believe the collaboration between Lower and Hooke to be an especially instructive term of comparison with the Italian scene. Their experiments showed that the motion of the lungs was not necessary to keep the animal alive, thus disproving the purely mechanical view of respiration, and that blood changed color in the lungs as a result of the presence of fresh air. In 1669 Lower published *Tractatus de corde item de motu & colore sanguinis*, in which the issue of the color of blood was given a prominent place in the title. Lower's treatise consists of five chapters, on the structure of the heart, its motion, the motion and color of blood, blood transfusion, and the passage of chyle into the blood. Since the heart is a muscle, Lower discussed the structure of muscles and, following Steno's example, includes several copper engravings of different muscles. My main concern here is with chapter three, in which he challenged Malpighi's and Borelli's interpretation of the lungs' purpose, arguing instead that blood cannot be better fragmented in the lungs than in the muscles. Rather, he believed that in the lungs blood was being mixed with air; fresh air was therefore essential to the animal not because of a mechanical operation, but because of a chemical one, as Lower hinted at when he argued that "wherever therefore a fire can burn sufficiently well, there we can equally well breathe." A large portion of the subsequent investigations by the English virtuosi was devoted to the chemistry of air and respiration.<sup>36</sup> In *Tractatus de corde* Lower reported his vivisection experiments with the two pairs of bellows and thanked Hooke for his assistance in the passage quoted in the opening of this section. It would be reductive, however, to see Hooke merely as the operator of the second pair of bellows; rather, Hooke contributed to those anatomical researches a

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<sup>36</sup> Steno's work is discussed below. Eyvind Bastholm, *The History of Muscle Physiology* (Copenhagen, 1950), 148, 159-160. Troels Kardel, *Steno on Muscles, Transactions of the American Philosophical Society*, 84.1 (1994), at 28. Lower, *De corde*, 168-171.

mode of mechanical thinking and experimenting for which he was one of the recognized masters.

## 6. Microscopy and Colored Injections: Swammerdam and Hudde

To this we shall add, that among all the kinds of microscopes which have been invented, none is better than that which has only one lens. But since we owe the benefit of this instrument or contrivance to Mr. Jan Hudde, one of the greatest mathematicians of our century and burgomaster of the city of Amsterdam, we esteem it our duty to do this renowned gentleman honour; and to give him public thanks for the favour he has done us in this respect.<sup>37</sup>

Swammerdam was the leading insect anatomist of the late seventeenth century. His work relied on an extraordinarily complex and refined set of techniques of fixation of the fluid and elusive internal parts of insects and microscopy that enabled him to gain access to a new world. While Malpighi had pioneered insect anatomy with his 1669 *De bombyce*, a treatise on the silkworm in which he attained remarkable results while refraining from explaining his techniques of investigation, Swammerdam made a point of explaining his own methods. His first work on the subject, the 1669 *Historia insectorum generalis*, was in press while he received a copy of Malpighi's treatise. At that stage Swammerdam had not mastered the art of microscopic anatomy at a level comparable to Malpighi's, but he did explain that a combination of lees of wine and vinegar in equal parts hardened the insects' members. He was soon to embark on a painstaking work aiming at emulating and eventually surpassing the achievements of his Italian rival.<sup>38</sup>

Swammerdam acknowledged the help he had received in microscopy by Jan Hudde, as the opening quotation shows. Hudde was a respected mathematician of the school of the Leiden professor

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<sup>37</sup> Jan Swammerdam, *Histoire générale des insectes* (Utrecht, 1682), 74; I have modified the translation in Swammerdam, *The Book of Nature, or the History of Insects* (London, 1758), 41.

<sup>38</sup> Swammerdam, *Histoire*, 74-75, 212. Abraham Schierbeek, *Jan Swammerdam. His Life and Works* (Amsterdam, 1974).

Frans van Schooten the Younger, together with Christiaan Huygens, Hendrik van Heuraet, and Jan de Witt. Van Schooten's mathematical career is associated with Descartes' *Géométrie*, for which he prepared the figures in the 1637 *editio princeps* and which he subsequently translated into Latin and expanded in 1649, 1659 and 1661. Besides working on algebra and the determination of maxima and minima, Hudde had also an interest in the problem of generation; possibly as a result of this he became engaged in the fabrication of lenses reported in the passage opening this section. That, however, was not the only acknowledgement to Hudde in Swammerdam's publications. In *Miraculum naturae*, a treatise of 1672 on the female organs of generation, he relied on colored injections and had the arteries colored in red by hand in the plates of some copies of his book (see Figure 7) to highlight the novel technique; in this case too he acknowledged Hudde's role, attributing to him the invention of the technique of injecting different colors to represent different humors well before Malpighi had used mercury injections in his 1661 *Epistolae*. Unfortunately little else is known about the contacts between Swammerdam and Hudde, but the little we know shows that the anatomist credited the burgomaster mathematician with two of the most significant among his techniques of investigation. Interestingly, just prior to the publication of *Miraculum naturae*, the anatomist Theodor Kerckring too praised the "noble mathematician and philosopher" Baruch Spinoza for having made a microscope for him.<sup>39</sup>

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<sup>39</sup> Edward G. Ruestow, *The Microscope in the Dutch Republic* (Cambridge, 1996), 30-1, 61, 112, 127n87, 143; Marian Fournier, *The Fabric of Life* (Baltimore, 1996), 147. Harold J. Cook, *Matters of Exchange* (New Haven, 2007), 284-285, 290; "Time's Bodies. Crafting the Preparation and Preservation of Naturalia," in Pamela H. Smith and Paula Findlen, eds., *Merchants and Marvels. Commerce, Science, and Art in Early Modern Europe* (New York, 2002), 223-247. Matthew Cobb, "Malpighi, Swammerdam, and the Colorful Silkworm: Replication and Visual Representation in Early Modern Science," *Annals of Science*, 59 (2002), 111-147, at 131-135; idem, *Generation. The Seventeenth-Century Scientists Who Unraveled the Secrets of Sex, Life, and Growth* (New York and London, 2006), 165-167. Theodor Kerckring, *Spicilegium anatomicum* (Amsterdam, 1670), 177-179.

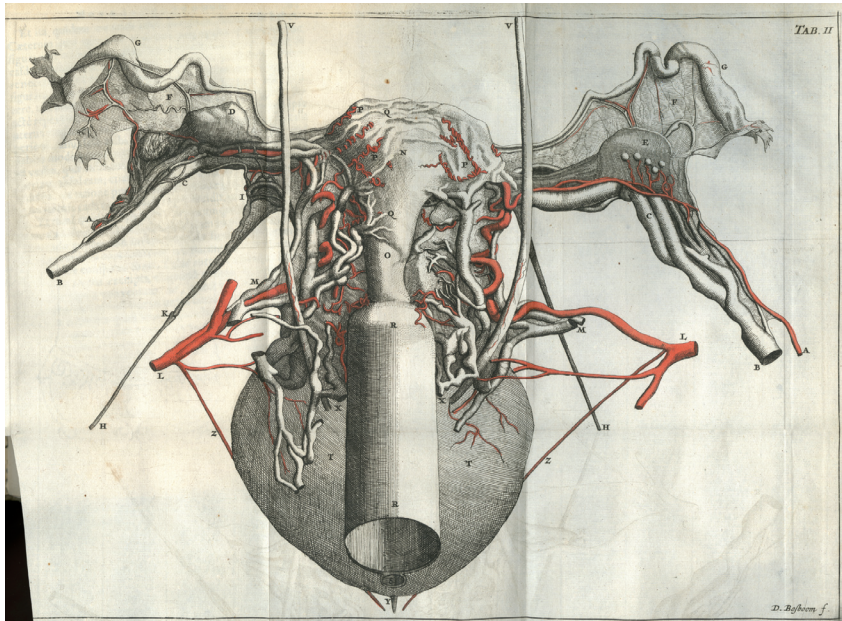


Figure 7. Swammerdam, *Miraculum naturae*: color injections of wax.

## 7. Vision and the Optic Nerve: Briggs and Newton

In fact that humor flowing in between (as the most learned friend Mr. Newton subjoins) rises up slightly towards the *simbrias* of the eyelids (just as water rises higher when it is closer to the edges of the vase).<sup>40</sup>

The science of optics and the anatomy of the visual organs have been tied since antiquity. In the period covered by this study, both Malpighi and the physician William Briggs at Cambridge performed

<sup>40</sup> William Briggs, *Ophthalmographia* (Cambridge, 1676; London, 1687), 17: “Humor enim ille interfluus (uti amicus doctiss. D. Newton supponit) versus ciliorum simbrias parum assurgit (sicut aqua in vase altius intumescit, dum a vasis marginis terminatur).” I am grateful to Alan Shapiro for having pointed to me to Briggs’s work and contacts with Newton. Alan Shapiro, ed., *The Optical Papers of Isaac Newton* (Cambridge, 1984), 590-593, especially nn. 8-9. Shapiro highlights the similarity in language between Briggs’s brief acknowledgement and a passage from Newton’s manuscript lectures called *Optica*.

dissections in front of mathematicians such as the astronomer Gian-domenico Cassini at Bologna and Isaac Newton. While we have few details of the collaboration between Malpighi and Cassini, apart from a deleted paragraph in the manuscript of Malpighi's posthumous *Vita*, the exchanges between Briggs and Newton are reported in several publications and in their correspondence as well.<sup>41</sup>

Briggs received his BA at Cambridge in 1667 and then studied medicine at Montpellier with Raymond Vieussens; in 1677 he received his Cambridge M.D. Briggs was Fellow at Corpus Christi between 1668 and 1682, when he became Fellow of the Royal College of Physicians. In 1676 he published at Cambridge *Ophthalmographia sive oculi ejusque partium descriptio anatomica*, a work in which—as the subtitle indicates—he provided a comprehensive anatomical description of the organ of vision, including a discussion of Mariotte's celebrated experiments on the blind spot. It was probably on the basis of its comprehensive treatment that it was included in the *Bibliotheca anatomica*. The first evidence we have of Briggs's contacts with Newton comes from this publication, in which he mentioned him in the passage reported in the opening quotation: Newton offered an explanation of the humidity of the eyes based on capillarity, a phenomenon that had recently come under scholarly attention.<sup>42</sup>

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<sup>41</sup> Biblioteca Universitaria, Bologna, Ms 936, I.B. Malpighi, *Vita*, f. 19r.: "Inter reliquos nostrae Accademiae Professores tunc temporis eminebat Praeclarissimus Dominus Jo: Dominicus Cassinus, qui praeter physicam, astronomicamque peritiam anatomiae studia colebat. Hic itaque interdum sectionibus anatomicis aderat, et praecipue in oculi indagine, unde non semel crystallino, vel etiam una cum vitreo humore ab ove eruto objectum in debita distantia auctum et inversum cum ipso spectatus sum, et supra objectum immediate positum apparebat. Quaedam quoque molibar circa harum partium naturam. Crystallinus igitur humor in bove exterius molior occurbat in medio autem lentem solidam et quasi cartilagineam habere videbas, in cuius centro ovalis inaequalisque concavitas conspiciebas. Humor vitreus igne tentatus licet ad crystallini naturam quo ad figuram, et diaphanitatem reduci videretur, totus tam in aquam tandem solvebas." See also *MCA*, 1: 72-74, at 74: Borelli to Malpighi, 4 March 1661.

<sup>42</sup> LeClerc and Manget, *Bibliotheca anatomica*, II, 1699, 173-185. On Briggs see the entry in the *Oxford Dictionary of National Biography* by Barbara Beigun Kaplan. R. Rutson James, *Studies in the History of Ophthalmology in England* (Cambridge,

Contacts between Briggs and Newton did not end with *Ophthalmographia*. In 1682 and 1683 Briggs published papers on vision in the *Philosophical Collections* and *Transactions*; his interest shifted from anatomical structures to the process of vision. In the first essay he argued that different portions of the optic nerves have different tensions depending on the way they are bent; he then compared the optic nerves to the strings of a viol vibrating in unison as a way to explain binocular vision. He also reported that in fishes—with the exception of whittings, which lack a decussation or crossing of the nervous fibers—the optic nerves are joined whereas in the chameleon they do not touch. In the second essay Briggs argued that the optic nerves remain distinct and they do not mix or blend; he then proceeded to discuss the objections he had received both when his paper was presented at the Royal Society and later through correspondence, including those by Newton. Despite some disagreement with Newton, Briggs's essays were translated into Latin and published together in 1685 as *Nova visionis theoria* at Newton's instigation with a preface by him in which he recalled having witnessed Briggs dissect the eye and display its muscles very effectively.<sup>43</sup>

The collaboration between Briggs and Newton follows a familiar pattern: the anatomist helped the mathematician with dissection whilst the mathematician offered physico-mathematical explanations. The case of Newton, however, is more complex in that we have evidence that in the mid-1660s he had reached a sophisticated under-

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1933), 74-83. Gómez López, "Malpighi and Atomism," 180-183; *Le passioni degli atomi* (Florence, 1997), 28-61, 82-93. Mirko D. Grmek, "Mariotte et la physiologie de la vision," in René Taton, ed., *Mariotte savant et philosophe († 1684)* (Paris, 1986), 155-184.

<sup>43</sup> William Briggs, "A New Theory of Vision," in *Philosophical Collections*, 6 (1682), 169, 170, 172, 176. On the earlier history of the optic chiasm, see David C. Lindberg, *Theories of Vision from al-Kindi to Kepler* (Chicago, 1976), *sub indice*. William Briggs, "A Continuation of a Discourse about Vision," *Philosophical Transactions*, 13 (1683), 171-182, at 175, 179 for Newton's objections. Isaac Newton, *Correspondence*, eds. H.W. Turnbull, A. Rupert Hall, Laura Tilling and J.F. Scott, 7 vols. (Cambridge, 1959-1977), 2:377-378, Newton to Briggs, 20 June 1682; *ibid.*, 2:381-385, 12 September 1682; Newton's preface to *Nova visionis theoria* is reported and translated in *ibid.*, 2:417-419.

standing of the path of the optic nerves, one surpassing Briggs's own work. In a manuscript dated by James McGuire and Martin Tamny to ca. 1665-6 Newton examined binocular vision with the help of experiments and anatomy. Some scholars have been attracted to this manuscript by his ill-advised self-experimentation involving pressing and deforming his eyeball with a bodkin and studying the apparition of colors as a result. The anatomical investigation showed the partial decussation of the optic nerve, namely that the nerve fibers from the left sides of both eyes join in the optic chiasm before going to the left side of the brain, whilst those from the right sides of both eyes join in the chiasm before going to the right side of the brain; Newton then proceeded to draw a number of conclusions from this anatomical feature. It is not known how he attained this result and whether it was due to collaboration with an anatomist or to his own investigations: in *Ophthalmographia* Briggs stated that while in the ray fish optic nerves are separate, in humans and quadrupeds they are most perfectly joined, without providing further details. Moreover, in those years Cambridge was an active anatomical center with scholars such as Walter Needham and Malachia Thruston. Newton's research testifies to his interest in anatomy; another early anatomical observation he performed in the kitchen of Trinity College, Cambridge, consisted in cutting the heart of an eel and observing the pieces beating in unison, an experiment not unlike that performed by William Harvey and mentioned in chapter four of *De motu cordis et sanguinis*.<sup>44</sup> Newton reported his findings in query 15 of the *Opticks*, where he argued that the optic nerves of animals that look the same way with both eyes cross in the way described above before entering the brain, whereas in animals that do not look the same way, such as fishes and the chameleon, they do not cross, cautioning "if I am rightly inform'd"—where

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<sup>44</sup> Cambridge University Library, ms 3975, published in James E. McGuire and Martin Tamny, *Certain Philosophical Questions* (Cambridge, 1983), 466-89, at 484-488; the manuscript is transcribed and reproduced in *The Chymistry of Isaac Newton*, <http://webapp1.dlib.indiana.edu/newton/mss/norm/ALCH00110/> Richard S. Westfall, *Never at Rest* (Cambridge, 1980), 93n76. Briggs, *Ophthalmographia*, 71-72. Stephen L. Polyak, *The Vertebrate Visual System* (Chicago, 1957), 108-109.

in all probability Briggs was the informant.<sup>45</sup> The 1699 edition of the *Bibliotheca anatomica* added some corrections to *Ophthalmographia*, though the partial decussation of the optic nerve is not among them, thus further highlighting the originality of Newton's contribution.

## 8. The Structure of Muscles: Steno and Viviani

To avoid that someone may attribute these observations to the intellect [*ingenio*] rather than experiences, I call as a witness my closest friend Vincenzo Viviani, mathematician to the Grand Duke, who was present as something more than a spectator to these and other investigations contained in this book.<sup>46</sup>

The Danish anatomist Nicolaus Steno seems to have become interested in muscles through his interest in the heart. In a letter to Leibniz Steno stated that when he was a student in Leiden he greatly admired Descartes but came to doubt his views through his own study of muscles and the heart. Cartesian views on the body were known through several of his works, starting from section five of the *Discours de la méthode*, but they became the focus of renewed attention in the aftermath of the Leiden publication of *Tractatus de homine* by Florentius Schuyf in the summer of 1662, the same year in which Steno published an important treatise on glands, *Observationes anatomicae*. At the same time he started investigating the motion of the heart, composing *Observationes circa motum cordis auricularumque et venae cavis*, an essay published with some later additions in his former teacher Thomas Bartholin's *Acta Hafniensia* for 1675: one of the observations on the heart is dated August 1662, the same month of the letter to Bartholin announcing the

<sup>45</sup> Isaac Newton, *Opticks* (London, 1730, reprinted New York, 1979), 346-347. As it happens, Briggs's claim is not correct: see Polyak, *Vertebrate Visual System*, 779-782, claiming that all vertebrates have partial or total decussation.

<sup>46</sup> Nicolaus Steno, *Elementorum myologiae Specimen* (Florence, 1667), in *Opera philosophica*, 2 vols. (Copenhagen, 1910), 2:119: "Ne verò quisquam ingenio potiùs, quàm experientiae haec attribuat, Amicissimum mihi Vincentium Viviani, Serenissimi Magni Ducis Mathematicum testem appello, qui hisce aliisque praesenti libro contentis plusquam spectator adfuit."





Figure 8. Steno, letter to Bartholin of 1663: earliest representation of a muscle.

appearance of *De homine*. In *De homine* and elsewhere Descartes had argued that the heart is very hot and expands because of the expansion of the incoming blood that is heated in it, a view Steno came to dispute. In the letter to Bartholin, Steno expressed his admiration for the illustrations of Descartes' brain but doubted that the contents of the illustrations could be found in any brain. Bartholin, by contrast, was more sympathetic to Descartes and thought that the dark color of the pineal gland supported Descartes' views about vision, since external images are clearer on the wall of a dark room.<sup>47</sup>

It was in the letter to Bartholin of April 1663, first published in the last volume of Bartholin's correspondence in 1667, that Steno announced his findings about the structure of muscles and of the heart. He argued that fleshy fibers do not extend from one extremity of the muscle to the opposite extremity, but rather they run parallel to each other transversally between the tendons: the structure of a muscle consists of two tendons AB and CD enclosing the fleshy fibers EE (see Figure 8). Steno also announced that the heart was a muscle, because "nothing is found in the heart which is not a muscle and nothing is absent in the heart which is found in a muscle, if you consider the essence of a muscle," a statement he repeated in the 1664 *De musculis et glandulis*; this treatise was first

<sup>47</sup> Nicolaus Steno, *Epistolae*, 2 vols., (Copenhagen/Freiburg, 1952), 1:366-369, at 367: Steno to Leibniz, November 1677. Thomas Bartholin, *Epistolae*, 4 vols. (Copenhagen, 1663-1667), 4:103-113, at 113, Steno to Bartholin, Leiden, 26 August 1662; also *ibid.*, 348-359, at 358, Steno to Bartholin, Leiden, 5 March 1663; *ibid.*, 359-363, at 360, Bartholin to Steno, 7 April 1663. Nicolaus Steno, "Ex variorum animalium sectionibus hinc inde factis excerptae observationes circa motum cordis auricularumque et venae cavae," *Acta Medica et Philosophica Hafniensia*, 2 (1673, published 1675), 141-147.



Figure 9. Steno, *De musculis et glandulis*: structure of a muscle.

published in Copenhagen and immediately thereafter in Amsterdam with a plate including tiny illustrations that had appeared as insets in an elaborate frontispiece of the Copenhagen edition: the figure of the muscle seen here differs from that of his letter to Bartholin, because Steno drew the fleshy fibers in the middle as the continuations and extension of the tendons (see Figure 9), whereas in 1663 they merely connected them. He presented his findings as the outcome of an observation during dissection: these results were expanded and rearranged in a new fashion in the text we are going to examine below. Steno criticized previous views—including Harvey's, whose name however he omitted—when he argued that whereas some had seen in the heart the seat of natural heat, the throne of the soul, a king or the sun of the body, he saw in it only a muscle.<sup>48</sup>

<sup>48</sup> Nicolaus Steno, *De musculis et glandulis observationum specimen* (Copenhagen, 1664); in the eighth conclusion in Steno, *Opera*, 1:177, Steno offered a vivid image

Following a query by his teacher Thomas Bartholin, Steno faced immediately the problem of contraction, because in general muscles respond to the will, whereas the motion of the heart is involuntary. His response was that in many other cases muscles move involuntarily, as in the larynx and the tongue. He argued that the heart does not have a special pulsatile faculty, but rather all muscles have the same ability to contract, something he believed had not been previously observed.<sup>49</sup> This solution did not end Steno's quest to understand muscles: for problems like the change of shape and volume during contraction he needed mathematics, and although he was already proficient in this area, he sought deeper knowledge.

Soon after his arrival in Florence early in 1666, Steno offered to visit Borelli at his lodgings in San Miniato to be instructed in geometry. Since Borelli was professor of mathematics at Pisa and his anatomical interests had been well advertised through Malpighi and Bellini and were well known at the Tuscan court, it was only natural that Steno would approach him. Borelli, however, was quite concerned because he was familiar with the quality of Steno's previous works and feared that the "oltramontano" wished to appropriate his findings. Muscle anatomy was one of Borelli's areas of interest: he claimed he had discovered the spiral structure of the cardiac muscle at Pisa in 1657, but he had been anticipated in print by Steno's 1664 *De musculis et glandulis*.<sup>50</sup> In the end, it is not surprising that Steno found in Viviani a more willing instructor. Viviani had been an assistant and disciple to Galileo and was involved in the posthumous edition of his works, excluding the *Dialogo*, in 1655-6; further, he was a respected mathematician who had published several works in geometry and mechanics. He did not share Borelli's anatomical interest but supported the project of applying

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of the structure of muscles by comparing it to the machine for planting poles of pile-dwellings.

<sup>49</sup> Steno, *De musculis et glandulis*, ninth conclusion in Steno, *Opera*, 1:177-179. See also Bartholin's letter of 25 July 1663, in *Epistolae*, 4:421-427, at 425.

<sup>50</sup> *MCA*, 1:260-261 and 318-319, Borelli to Malpighi, Florence, 12 June 1665 and 17 July 1666. *MOB*, 21. Troels Kardel, *Steno on Muscles* (Philadelphia, 1994), 67, 201, 205.

geometry and Galileo's method to new domains; moreover, Viviani disliked Borelli and did not miss his chance to harm him by offering his services to Steno.

In 1667 Steno published *Elementorum myologiae specimen, seu musculi descriptio geometrica*, a book that included also the report of dissections of sharks obtained from the Grand Duke Ferdinand II. Viviani witnessed Steno's dissection of the shark, as the passage from the opening quotation shows, but his role must have been far more significant in the first and major part of Steno's treatise on myology. Since the acknowledgement to Viviani appeared in a different portion of the treatise, the recent edition and translation of Steno's works on muscles omits it, obscuring in this way a crucial tool for understanding the background to Steno's treatise and the way he structured it. Steno's dedication to the Grand Duke provided a spirited defense of the role of mathematics in anatomy, especially for the explanation of the structure and operation of muscles:<sup>51</sup>

In this dissertation I wished to show that unless myology becomes part of mathematics, the parts of a muscle cannot be distinctly designated, nor can its motion be considered adequately. And why should we not give to the muscles what astronomers give to the sky, geographers to the earth, and, to take an example from the microcosm, what writers on optics concede to the eyes?

Steno went even further, this time echoing Cartesian and Gassendist themes: "But why do I claim for the muscles what is due to the entire body? Our body is an organ composed of one thousand organs; whoever believes that its true cognition can be attained without the help of mathematics, must also believe that there is matter without extension, body without figure." Despite this apparent endorsement, Steno was far from being an unreserved admirer of Descartes, as we have seen above. Moreover, in his treatise on the anatomy of the brain addressed to the members of the Paris academy of the diplomat and royal librarian Melchisédech Thévenot, for example, Steno had challenged several Cartesian tenets, and even

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<sup>51</sup> Steno, *Opera*, 2:154. The quotation is from the non-numbered page from the dedicatory letter to the Grand Duke; I have modified the translation in Kardel, *Steno on Muscles*, 82-85.

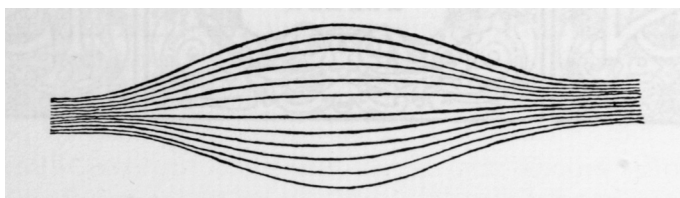


Figure 10. Steno, *Specimen*: the old inaccurate representation of muscles.

his *Elementorum myologiae specimen* includes a letter to Thévenot criticizing those followers of Descartes unwilling to accept that the heart is a muscle, probably a reference to discussions at Thévenot's academy and possibly to his teacher Sylvius: as we have seen above, this may well have been his initial motivation to work on the subject.<sup>52</sup>

Steno starts by denying that the traditional structure of muscles (see Figure 10) occurs in nature. Both the structure of the treatise and its contents reveal the author's passion for geometry: Steno believed that a key notion necessary to understanding muscles was that of motor fiber, shown here as a three-dimensional representation, where ABCDEFGH is the parallelepiped of the fleshy part, and DAMICBLK, EHNQFGOP are the quadrangular prism representing the tendons (see Figure 11). Following the example of geometers, Steno began with definitions, starting from that of motor fiber, followed by forty-three others, then by hypotheses, lemmas, propositions, and corollaries. The illustrations in the treatise leave no doubt as to his geometric bend: a proposition argues that a muscle swells when it contracts (see Figure 12). On the left is a non-contracted muscle, on the right the same muscle contracted. Notice that these figures are a two-dimensional or cross-section representation of the motor fiber shown in perspective in figure 11. Steno argued that the thickness CS of the contracted muscle is greater than the thickness CR of the non-contracted one, where CS and CR are perpendicular to ID and FR, respectively. The volume,

<sup>52</sup> Kardel, *Steno on Muscles*, 200-201; Nicolaus Steno, *Discours sur l'anatomie du cerveau*, originally delivered in 1665 (Paris, 1669); *Lectures on the Anatomy of the Brain* (Copenhagen, 1965), with an introduction by G. Scherz.

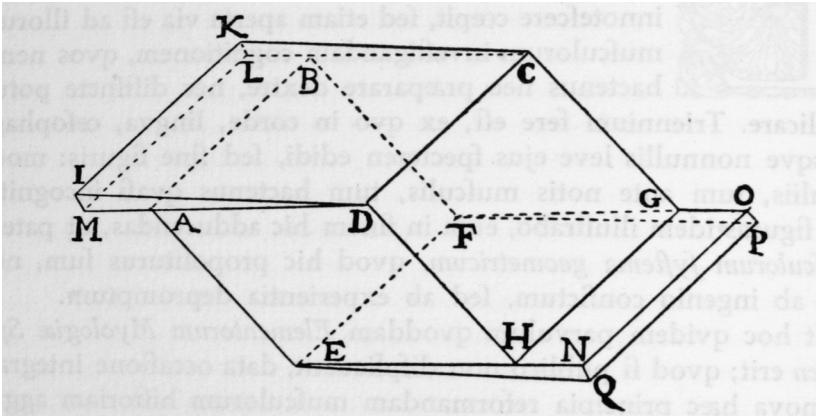


Figure 11. Steno, *Specimen*: correct structure of a muscular motor fiber.

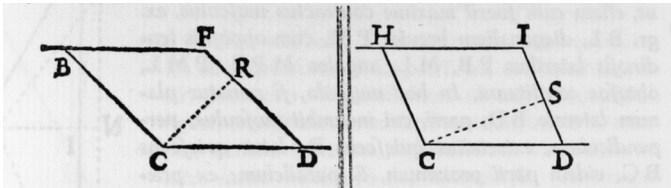


Figure 12. Steno, *Specimen*: the swelling of muscles.

however, is the same because the basis and height of the parallelogram do not change. This is a key point of the treatise because Steno wished to show mathematically that a muscle contracts and swells without any overall change in volume and without any incoming matter but only as a result of the sliding of the tendons. The nail in the coffin of the old view would have been represented by the proof that muscle fibers can contract even after nerves and blood vessels have been severed, but Steno left this coup de grâce for another occasion.<sup>53</sup>

A closer analysis of the text shows another role for the mathematical tradition, this time from a Galilean perspective. In *Two New*

<sup>53</sup> Kardel, *Steno on Muscles*, 25-26; 149, 163, 165. Brown, *Mechanical Philosophy*, 95-99. Bastholm, *History*, 158, inaccurately states that Steno “overlooked the circumstance that [a] muscle naturally becomes thicker when each muscle fiber becomes shorter.”

*Sciences* (1638) Galileo had put forward a new mathematical science of motion in axiomatic form. Initially he had presented his science purely as a mathematical construction based on a definition and a postulate dealing with uniformly accelerated bodies, or bodies whose speed increases in proportion to the time of fall. In 1638 the postulate was justified by some observations, including some experiments; later, pressed by young Viviani, Galileo found a mechanical proof without any experiment that appeared in the 1656 posthumous edition of his works. In both editions of his work he argued only at a later stage that his mathematical construction corresponds to nature. Galileo could make this claim by means of his celebrated experiment with a ball rolling down an inclined plane, showing that falling bodies traverse distances proportional to the square of the times, as implied by uniformly accelerated motion. Thus in Galileo's elaborate and rather contrived presentation the inclined plane experiment did not have a foundational role but rather served the purpose of anchoring to nature a mathematical theory that was coherent in its own right.<sup>54</sup>

Steno's strategy shows some analogies with Galileo's. Steno presented his views first in an abstract, geometrical fashion. Although he hastened to clarify that his system was not manufactured by the intellect [*ingenio*], but produced by experience, it was only at a later stage, after he had completed the presentation of his *Elementorum myologiae specimen*, that he wished to demonstrate the certainty of those elements by means of examples produced from nature herself. This he did not by means of an experiment, as Galileo had done, but simply by means of the figures: he wished merely to show, rather than explain, the figures of different muscles, because the matter was so evident that *sola inspectio sine explanatione* sufficed. Steno's treatise includes several plates: whereas the later ones on the anatomy of the shark are copper engravings, which was the privileged, more expensive and most accurate means of anatomical reproduction, those on muscles are woodblock prints. Steno stated that

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<sup>54</sup> Galileo Galilei, *Two New Sciences*, transl. by Stillman Drake (Madison, 1974), 162-164, 171-175. Domenico Bertoloni Meli, *Thinking with Objects* (Baltimore, 2006), 97-98, 118-119.

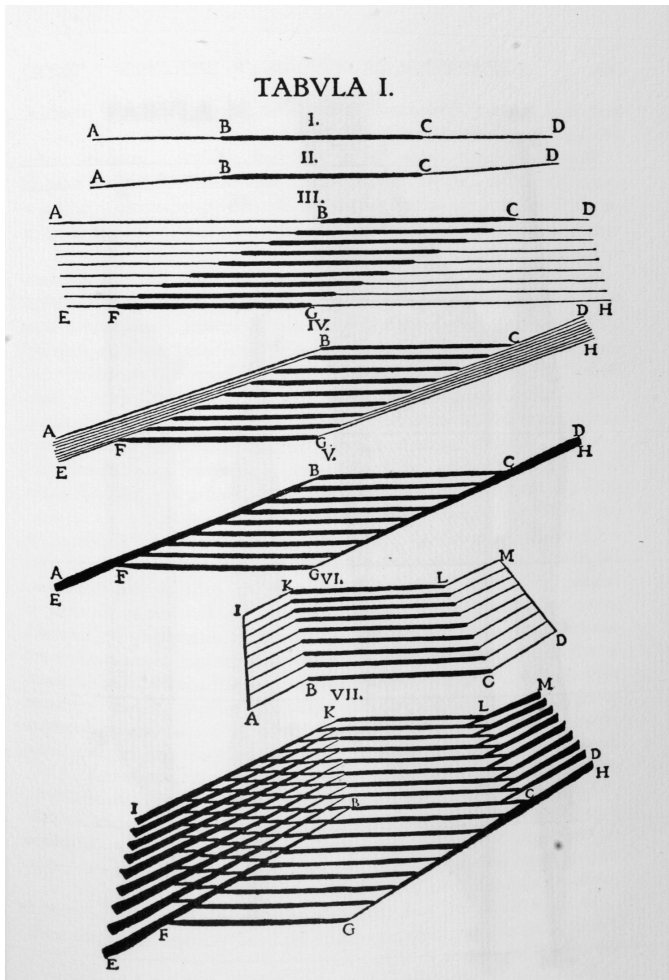


Figure 13. Steno's life-size representation of a muscle with nine fibers.

they were drawn life-size so as to show the real dimensions and the exact angles among the muscle fibers: clearly for this purpose wood-block prints were sufficient. It is especially pleasing to see Steno's geometrical way of studying and conceiving muscles embodied in the art form adopted. Figure 13, from plate I, for example, shows a muscle with nine motor fibers first straight and then bent, whereas figure 14, from plate III, shows several examples of muscles, includ-



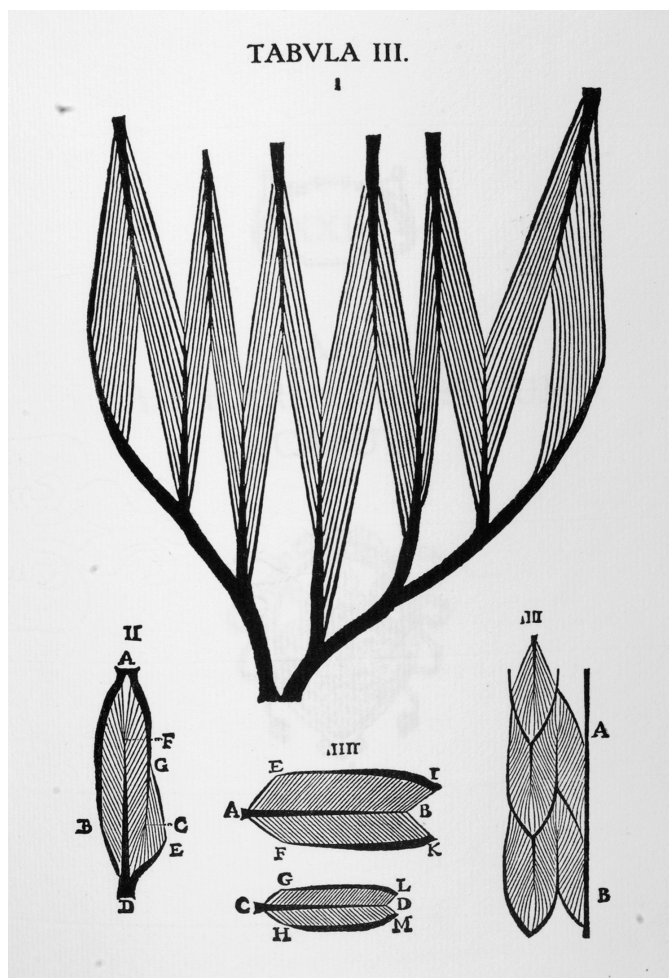


Figure 14. Steno's life-size representation of different muscles.

ing the deltoid at the top (I) and the major claw of a lobster at the bottom (III).<sup>55</sup> Thus one could argue that Steno's images of muscles at the end of his treatise serve the role of Galileo's inclined

<sup>55</sup> Kardel, *Steno on Muscles*, 158-73. Martin Kemp, "The Mark of Truth': Looking and Learning in some Anatomical Illustrations from the Renaissance and Eighteenth Century," in William F. Bynum and Roy Porter, eds., *Medicine and the Five Senses* (Cambridge, 1993), 85-121, esp. 101.

plane experiment: those figures (see Figures 13, 14) from the concluding plates are drawn from nature and are not to be confused with the geometric diagrams in the body of the book (Figures 11, 12). Yet their profound similarities showed that Steno's geometrical propositions corresponded to nature. It is hard to imagine that Viviani, besides instructing Steno on mathematics, would not have been involved in methodological discussions on the presentation of Steno's *Specimen*, given that Viviani was especially concerned about these matters and had pressed Galileo to provide a more solid foundation for his new science. Steno's presentation was wholly unusual in anatomy: Lower's later presentation in *Tractatus de corde* is entirely traditional, implicitly highlighting how contrived and unusual Steno's was. In addition, occasionally Steno's language too, as when he talks of motor fibers *aequaliter* and *inaequaliter aequales*, suggests some familiarity with the mathematical tradition of the *calculatores*, one with which Viviani and Galileo were well acquainted.<sup>56</sup> Thus uncovering the collaboration with Viviani has provided us with the tools for reading a text whose structure and style had so far eluded interpreters.

### Concluding Reflections

Although the examples we have discussed are far from exhausting the cases of collaboration between anatomists and mathematicians, let alone their broader cooperation at different levels, the results attained are quite striking. Let us recapitulate them.

Overall, the focus was on techniques of investigation such as microscopy and injections—including injection of air or insufflation—and on interpreting the operations and purposes of structures: Pecquet relied on recent experiments on the Torricellian tube to highlight the importance of *elater* or elasticity; Malpighi and Bellini carried out their investigations on the assumption that dis-

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<sup>56</sup> Kardel, *Steno on Muscles*, 106-109 and 158-159. Edith Sylla, "Galileo and the Oxford *Calculatores*: Analytical Languages and the Mean-Speed Theorem for Accelerated Motion," in William Wallace, ed., *Reinterpreting Galileo* (Washington, D.C., 1986), 53-108.

covering the microscopic structure of an organ would be crucial to understanding its mechanical operation, a task performed by Borelli; at one point Borelli suggested a role for capillary action, much like Newton did for Briggs; Willis and Wren followed very much the same pattern in discussing the uses of the parts, though Willis relied on Wren's drawing skills and injection techniques as well; injections and microscopy were the basis of Hudde's work with Swammerdam; Lower and Hooke relied on previous anatomical findings and performed experiments in order to understand the operations of the lungs and the purpose of respiration, much like Harvey had relied on previous structural anatomical findings—such as the *ostiola* or valves in the veins—in order to provide a radically new account of the motion of blood. Harvey too had relied on or at least mentioned a range of techniques such as ligatures, magnifying lenses, injection and insufflation; unlike Harvey, however, the new investigators rejected the faculties and sought to provide a purely mechanistic understanding. The case of Steno is unusual among those we have studied in that he relied on Viviani's geometrical and methodological assistance, since geometry was essential to his novel account of muscular contraction and arguably the usage of mathematics in the study of nature required an appropriate method of presentation. Yet in this case, too, understanding the structure of muscles was a prelude to grasping their mode of operation in contraction. Thus the collaborations we have investigated involved the refinement of injection techniques and the deployment of novel ones—such as microscopy—in the attempt to uncover structures and understand their mechanical modes of operations and purposes.

An influential textbook in the history of science states:<sup>57</sup> “Iatromechanism did not arise from the demands of biological studies; it was far more the puppet regime set up by the mechanical philosophy's invasion. ... One can only wonder in amazement that the mechanical explanations were considered adequate to the biological facts, and in fact iatromechanics made no significant discovery what-

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<sup>57</sup> Richard S. Westfall, *The Construction of Modern Science* (Cambridge, 1971), 104. I wonder whether Westfall's language in the first part of the quotation was reminiscent of the Vietnam War.

soever.” Although at first one may sympathize with Sam Westfall’s impatience towards mechanists piling speculation upon speculation, matters were more complex. In some instances, as with Pecquet, anatomists profitably employed mechanical notions, such as pressure and elasticity, in the explanation of the motion of chyle and in the account of the motion of blood through the arteries. More generally, the mechanists’ attempt to dispose of the faculties of the soul as an explanation of how organs operate, led them to seek with renewed enthusiasm the specific structural organization and mode of operation of those organs by means of the microscope or other devices from syringes to bellows.

Art historians and historians of science have long appreciated the significance of the alliance between medical men and artists in the sixteenth century, leading to startling representations of plants and animals in such works as *Herbarum vivae eicones* (1530), a project conceived by the publisher Johann Schott with texts by the Berne’s town physician Otto Brunfels and illustrations by Albrecht Dürer’s student Hans Weiditz; *De historia stirpium* (1542), conceived and written by the Tübingen professor of medicine Leonhard Fuchs with illustrations drawn from nature by Albrecht Meyer, transferred to woodblocks by Heinrich Füllmaurer, and cut into the wood by Veit Rudolf Speckle; and *Humani corporis fabrica* (1543) by the Padua professor of anatomy and surgery Andreas Vesalius with illustrations by an unknown artist in Titian’s circle.<sup>58</sup> Similarly, the seventeenth century brought a flourishing of anatomical investigations in which collaboration played a central role: from Pecquet to Steno, collaboration was a key feature of anatomical research that generated new questions and methods of investigation showing remarkable creativity and leading to a new understanding of the structure and operations of the body. Much like sixteenth-century collaborations are relevant to the history of art as well as the study of nature, seventeenth-century ones are relevant to the history of anatomy as well as of science.

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<sup>58</sup>) Brian Ogilvie, *The Science of Describing* (Chicago, 2006), 192-203. Gill Saunders, *Picturing Plants. An Analytical History of Botanical Illustration* (Berkeley, 1995), 17-40.

While significant in their own right, the cases studied in this essay bear a broader message: they argue against a sharp demarcation in the seventeenth-century transformations of knowledge between the mathematical and medical disciplines. When unraveling the intellectual world in the seventeenth-century, we can no longer separate the history of anatomy from the history of science as if anatomists and physicians inhabited a different world from not only mechanical and experimental philosophers, but also mathematicians.