RESEARCH ARTICLE

Forensically reconstructing biomedical maintenance labor: PDF metadata under the epistemic conditions of COVID-19

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Abstract

This study examines the documents circulated among biomedical equipment repair technicians in order to build a conceptual model that accounts for multilayered temporality in technical healthcare professional communities. A metadata analysis informed by digital forensics and trace ethnography is employed to model the overlapping temporal, format-related, and annotation characteristics present in a corpus of repair manual files crowdsourced during collaborations between volunteer archivists and professional technicians. The corpus originates within iFixit.com's Medical Device Repair collection, a trove of more than 10,000 manuals contributed by working technicians in response to the strain placed on their colleagues and institutions due to the COVID-19 pandemic. The study focuses in particular on the Respiratory Analyzer subcategory of documents, which aid in the maintenance of equipment central to the care of COVID-19 patients experiencing respiratory symptoms. The 40 Respiratory Analyzer manuals in iFixit's collection are examined in terms of their original publication date, the apparent status of their original paper copies, the version of PDF used to encode them, and any additional metadata that is present. Based on these characteristics, the study advances a conceptual model accounting for circulation among multiple technicians, as well as alteration of documents during the course of their lifespans.

1 | UNDERSTANDING BIOMEDICAL REPAIR WORK DURING COVID-19

This study examines the documents circulated among biomedical equipment repair technicians in order to build a conceptual model that accounts for multi-layered temporality in technical healthcare professional communities. A metadata analysis informed by digital forensics and trace ethnography is employed to understand the overlapping temporal, format-related, and annotation characteristics present in a corpus of device repair manual files, crowdsourced in the course of collaborative efforts between volunteer archivists and professional technicians in response to the COVID-19 pandemic. The findings demonstrate that device repair manuals often travel through multiple steps of mediation between the time of their initial publication and their eventual usage by technicians, including the hand annotation and scanning of paper documents, encoding as PDF files, porting forward into newer versions of PDF, and the addition (or removal) of new content over time. By advancing a conceptual model that accounts for multiple stages of such intervention, this project contributes to the study of working professionals' personal information practices and enables a more accurate assessment of the information needs associated with maintaining medical equipment—especially those related to working with devices and documents from a wide variety of temporal origins. In the conclusion, I summarize these steps of

intervention in terms of initial publication, print annotations, digitization, and porting forward. Existing information practices, as reconstructed during the analysis, may present opportunities for information specialists' support in terms of navigating intellectual property restrictions, comparing multiple editions of a file, and understanding the hardware/software operating environments within which maintenance and repair activities occur.

1.1 | Introducing the iFixit medical device repair manual collection

The corpus of documents used in this study originates within iFixit.com's Medical Device Repair collection, a crowdsourced trove of more than 10,000 device repair manuals contributed by working technicians in response to the strain placed on their colleagues and institutions due to the 2020–2021 COVID-19 pandemic. The study focuses in particular on the Respiratory Analyzer subcategory of documents, which aid in the maintenance of equipment central to the care of COVID-19 patients experiencing respiratory symptoms. As of its initial publication in May 2020, the published collection included 40 documents related to respiratory analyzers, which are selected for analysis because they are simultaneously critical to the treatment of severe COVID-19, while also widely used for general inpatient purposes. This combination of pandemic-specific and general-purpose significance makes respiratory analyzers a category of device particularly well-suited as a point of entry for studies seeking to understand the contours of medical maintenance labor in general, although the collection itself has been assembled due to epistemic shifts brought on by the pandemic.

The 40 documents associated with Respiratory Analyzers in iFixit's collection, accessed by searching "Respiratory Analyzer Repair" from the iFixit home page or navigating directly to https://www.ifixit.com/Device/Respiratory_Analyzer (see Figure 1), are examined and quantified in terms of their original publication date, the apparent status of their original paper copies, the version of PDF used to encode them, and any additional metadata or bibliographic features. After examining these document characteristics, the study turns toward developing a conceptual model that accounts for circulation of documents among multiple technicians, as well as alteration of documents during the course of their lifespans. A conceptual model in turn can be used to guide future development of information systems and interventions designed to support work in a given field (Jett, Sacchi, Lee, & Clarke, 2016). The values of such a model are shared among researchers who can use it as a theoretical

foundation for both future studies and the provision of effective support for technicians, as well as technicians who can use the model to better understand and plan their own daily work.

In order to understand the ways that repair manuals and other forms of documentation are used within a professional community of technicians during COVID-19, this study asks the following research questions:

RQ1: What traces of labor are recorded in digital biomedical repair manuals?

RQ2: How do the traces of labor recorded in digital documents reflect the unique epistemological conditions of working technicians during COVID-19?

1.2 | Background

Defined most broadly, biomedicine is "a branch of medical science, which is based on the application of the principles of natural sciences, especially biology and biochemistry to clinical practice" (Roos & Hedlund, 2016, p. 898). One crucial element of this definition that should be emphasized is its combination of science and practice. The field of biomedicine is primarily valuable to the broader social world insofar as it applies scientific knowledge to the actual provision of medical care. In other words, biomedical research activities are not motivated by the construction of knowledge alone. Instead, the construction of knowledge serves a broader effort to prevent or cure diseases (Roos & Hedlund, 2016, p. 898). Thus in addition to encompassing the knowledge work of scientific research and development, biomedicine also entails significant engagement at the point of care with practitioners, patients, facilities, and all of the material accoutrements implicated therein. As such, the practice of biomedicine is highly dependent upon technical labor related to maintenance and repair of necessary equipment.

The labor of maintenance is largely out of sight when equipment and organizations are running smoothly. In a study concerning audiovisual (A/V) preservation labor in academic libraries, for example, Lischer-Katz (2019) has shown that technical labor is "generally made invisible" during day-to-day operation (Lischer-Katz, 2019, p. 213). As a result, maintenance labor becomes far more apparent during periods of malfunction or emergency. Thus the present study has been enabled in part by the ongoing COVID-19 pandemic, as well as iFixit.com's response to it, which has made the contours of biomedical maintenance labor more apparent by occasioning collaborative archival work between both working technicians and volunteer processing archivists.

The task of compiling, organizing, and processing iFixit's collection of medical device documentation began

with a call from iFixit founder Kyle Wiens (Wiens, 2021). This call prompted working biomedical technicians around the world to contribute tens of thousands of documents, which a volunteer team of approximately 200 proceeded to process and organize. Volunjteers' work was accomplished using a custom-built web application, where volunteers created folders and subfolders in progressively more specific categories, beginning with device type (e.g., "ventilator"), moving into manufacturer, and device name (Medical Device Page Project Guidelines, n.d.). Files were generally removed in cases where duplicates were present, but documents often possess subtly unique traits that made the work of identifying duplicates less than straightforward. This phenomenon is further discussed in the "Findings" section below. It is worth noting at this juncture that the archival labor of making these documents available to the public involved several steps of interpretation and intervention, although this paper's main focus relates more to understanding and making visible the longer standing labor and information practices of biomedical repair technicians.

One major challenge that faces any effort at better understanding the information work of both biomedical technicians and volunteer archivists lies in the distributed and tacit characteristics of their practical knowledge. As noted in Julian Orr's (1996) canonical account of workplace technical and information practices, technical work is often deeply situated within the context of a particular environment, with idiosyncratic combinations of equipment and personnel working together to make the information needs of working technicians highly variable and site-specific. As Orr summarizes, "individual machines are quite idiosyncratic, new failure modes appear continuously, and rote procedure cannot address unknown problems" (Orr, 1996, p. 2). Orr describes the technicians' response to such unpredictable circumstances as a "continuous, highly skilled improvisation within a triangular relationship of technician, customer, and machine" (Orr, 1996, p. 1). In other words, the complex interplay of devices, people, and circumstances makes working knowledge perennially tentative and malleable. The present study also introduces another key resource that technicians may refer to when attempting to address this fragile, improvisatory set of circumstances: print documentation. And as the analysis shows, print documents are subject to the same kinds of changing, improvisatory practices as technical labor writ large.

Yet while Orr and Lischer-Katz's studies focus on photocopier technicians and A/V preservationists, respectively, this study expands the purview of existing workplace studies to focus on biomedical labor, with additional consideration given to the impact of crisis circumstances such as the COVID-19 pandemic. These contexts bring issues surrounding workplace information practices into clearer-than-usual focus, in the sense that they highlight the role of activities and personnel often hidden behind the scenes. Crises can be defined as "events or situations that are unwanted, unexpected, unprecedented, and almost unmanageable, and thus provoke widespread disbelief" (Rahmi, Joho, & Shirai, 2019, p. 716). In other words, crises push the limits of what can be understood and addressed under an organization or society's normal operating conditions. As a result, crises also prompt re-evaluation and re-orientation of many life and work habits. In the particular case of biomedical technicians operating during the COVID-19 pandemic, crisis conditions are what prompted the unprecedented collaborative efforts between technicians and archivists to share, organize, and publish technical documents via iFixit. Although the main goal of this collaboration was direct support to working medical professionals, one additional side effect has been the construction of a corpus containing documents that maintain traces, such as notes and metadata, accrued during their past interactions with technicians.

1.3 | Event epistemologies and intellectual property

Changing circumstances around knowledge and work during a crisis impact the way that technicians and laypeople alike respond to the world around them. Finn (2018) understands the particular types of knowledge-related behaviors that emerge during such a process to be emblematic of broader emergent "event epistemologies" (Finn, 2018, p. 2), or ways of knowing and responding to an event. In the present study, technicians and archivists have come to understand the role of technical documents differently during the COVID-19 pandemic than they did in the past. One key area of significance for this epistemological shift is related to intellectual property: technicians and information workers more broadly have come to understand access to information and access to documents as a public good that supersedes prior restrictions preventing their open sharing and publication.

The process of understanding information as a public good certainly does not originate within response to the COVID-19 pandemic, nor even in crisis response more generally. Instead, a movement for repair access has been growing throughout the early 21st century. Yet whereas previous campaigns in favor of repair rights have emphasized consumer electronics and information's general potential as a commonly owned resource (Graziano & Trogal, 2017), changing circumstances related to the

crisis of a viral pandemic have also changed the epistemological relationship between repair, documentation, and the public good. As one biomedical engineer summarized for *WIRED* magazine, "If [an] iPhone isn't fixed, you're not going to have a phone... If you don't fix a [biomedical device], the patient is dead" (Goode, 2020). The shift from repair as a topic of general consumer protection to repair as a life-or-death conflict reflects the particular event epistemology of response to COVID-19, in which knowledge about repair and maintenance assumes heightened status.

The changing epistemic conditions surrounding repair have shifted debates about the right to repair in several distinct yet overlapping ways. What began as a series of campaigns citing general ecological and economic benefits to consumer electronics repair, especially in poor communities and the global south, has taken on a higher profile in the global north as the pandemic increases pressure on comparatively more wealthy populations. For example, iFixit founder Kyle Wiens once justified his website's mission in terms of ensuring that "people who require access to affordable technology around the world will be able to buy a cheaper, refurbished computer" (Wiens, 2015, p. 135), appealing specifically to the need for technology access in impoverished communities. More recently, however, members of the information science community have argued that "the COVID-19 pandemic [makes] the fragility of our infrastructures frighteningly clear" (Shankar, Jeng, Thomer, Weber, & Yoon, 2020, p. 2). Attention paid to the informational and intellectual property dimensions of biomedical labor has increased accordingly.

Within the biomedical field more specifically, the largest publicly accessible collection of medical device documentation prior to the new iFixit project was Frank's Hospital Workshop, a project containing about 4,500 repair manuals, run by a single moderator in Tanzania, and targeted specifically at developing nations (Goode, 2020). The COVID-19 pandemic, in contrast, has jumpstarted increasing concern for access to medical repair resources in richer nations, with a number of U.S. state treasurers pleading with device manufacturers to make documentation more accessible (Matthews, 2020). During the pandemic, legal scholars and lawmakers increasingly understand crisis conditions to constitute a state of exception to normal intellectual property restrictions (Sarnoff, 2020). Although the present study does not focus on intellectual property per se, such conditions *have* played into the changing event epistemologies produced by COVID-19, and therefore in enabling the collaborative work of assembling the corpus of documents under analysis.

The event epistemology surrounding COVID-19 has impacts on information practices at large, not just on biomedical labor, and this change has been acknowledged in existing literature seeking to respond accordingly (Xie et al., 2020). In developing a more comprehensive understanding of biomedical repair labor, this study responds not only to the specific conditions of COVID-19, but also to the need for a deeper understanding of the ways that information resources like repair manuals are distributed, modified, and used in biomedical contexts. As such, this study begins from a belief that "like all infrastructure, the human and technical systems that facilitate knowledge production remain invisible until they break down" (Shankar et al., 2020, p. 2). In response to the epistemic shift produced by this sudden change in information visibility, this study aims to highlight information practices that are, like many COVID-19 response activities, "important to not only this one particular crisis—COVID-19—but also any global health crisis" (Xie et al., 2020, p. 1420).

1.4 | Crisis and disaster

Existing studies concerning information behavior during crisis have been largely oriented around response to natural disasters (Finn, 2018; Finn, Srinivasan, & Veeraraghavan, 2014; Rahmi et al., 2019). Yet while natural disasters are often relatively localized in terms of geographic impact, global health crises "are unique in that they can spread far, and fast, and have global impacts" (Xie et al., 2020, p. 1420). The global scope of COVID-19 makes its impact on biomedical technicians global as well, prompting collaboration on a previously unprecedented scale. By examining the traces of biomedical labor inscribed upon digital documents, this study contributes increased knowledge about the reliability, timeliness, and compatibility of documents with various technical and social configurations. In the findings, I emphasize the ways that PDF metadata can attest to the type of hardware and software used by technicians, as well as the temporal paths that documents take between initial publication and their subsequent circulation.

Existing conceptual models in the area of collectively generated archival collections and emergency information resources have been successful in creating guidelines for collection creation, as well as in understanding official government and NGO responses. Howard Besser's work on creating an archive of digital materials related to Occupy Wall Street introduces a conceptual model for processing collections when "there is no easy way to control for quality, file format, or metadata" (Besser, 2013, p. 32). There are clear parallels between the emergent qualities of Occupy and those of an ad-hoc crisis response, yet Besser's solution is one of developing

"smart ways to harvest metadata and analyze files, as well as to influence the behavior of potential contributors" (Besser, 2013, p. 33). Rather than aiming to *influence* behavior, the current study aims to *understand* behavior, focusing on *existing* information practices rather than potential practices. Other scholars have also described currently existing practices that aim to understand changes in digital objects over time, but these studies have most often done so in cases where the changes are officially documented by an authoritative entity (Gursoy, Wickett, & Feinberg, 2019). The present study works instead in a context where changes are not documented and there is no centralized authority responsible for maintaining the objects. While existing conceptual models of information practices related to both crisis response and changing digital objects generally assume that some centralized authority exists to coordinate the information response to complex circumstances, this study differs by responding to the specific event epistemology instantiated by COVID-19, in which a global response is characterized by its piecemeal, decentralized character.

1.5 | Text and digitization

In dealing with digitized versions of print publications, this paper builds on existing studies within the fields of bibliography and book history that have also used the material characteristics of media objects as a window into the practices of authorship, reproduction, and reading pervasive within a given social or historical milieu.

Existing studies concerning the bibliographic features of digitized documents provide a number of useful conceptual foundations for the present study, and the present study in turn extends these ideas into more recent historical contexts. Bonnie Mak (2014) has shown that digitized documents can operate both as representative copies of their source material as well as manifestations of "current perceptions about the past" at play in particular decisions about the precise forms and processes employed (Mak, 2014, p. 1515). Building on this assertion, I also argue that the objects of past digitization efforts (such as manuals digitized many years ago) can be analyzed as evidence of past attitudes about technical labor. More recent digitizations are, as Mak might say, "the materialization of a 21st century perception" about that object as well (Mak, 2014, p. 1516). Analysis of maintenance manuals for the present study has shown that maintenance technicians' digitization practices have changed over time as well. These findings echo Ryan Cordell's (2017) assertion that scholars must understand mass digitized texts not as static, authoritative objects, but rather as "assemblages of new editions, subsidiary editions, and impressions of their historical sources" (Cordell, 2017, p. 190).

Another dynamic that the present paper notes when examining the proliferation of digitized text is the presence of annotations and alterations made by readers. Within book history and textual studies, the subfield of marginalia studies treats these alterations as an aid to dutiful interpretation of a text a certain times, or augmentation of a text with to correct it with additional knowledge at others (Jackson, 2001, p. 42). Generally speaking, readers' annotations to a text help to situate that text within a living social context (Sherman, 2010). Yet while textual studies have most often addressed these phenomena in the context of codex-bound books that predate digital media, the present study shows how annotations take on a layered temporal dimension in other contexts as well.

2 | THEORY AND METHODOLOGY

This study's treatment of digital sources and their evidentiary value is built on the theoretical framework of digital forensics, which in turn informs a methodology based on trace ethnography. In short, this study begins from the assumption that information users' actions leave subtle inscriptions on digital objects that can attest to their activities when interpreted appropriately. Based on this assumption, the study aims to develop a rich description of information activities based on the traces left behind by such activities.

Digital forensics are a set of techniques originating within law enforcement and legal discovery, yet increasingly deployed within archival processing as well, in order to detect potentially sensitive information and to ensure that objects have not been altered during handling (Lee, Woods, Kirschenbaum, & Chassanoff, 2013). Forensic investigation techniques can also note details of an object's production and circulation processes, as well as information about how a file was treated over the course of its lifespan, even when those features are not acknowledged in extant documentation (Ries, 2018). As a result, digital forensics techniques constitute a valuable approach to recovering knowledge about behaviors that have already taken place, or that have taken place in contexts where efforts at observation could encounter problems related to access, intellectual property, privacy, or safety. In the case of biomedical device maintenance and repair, such activities have taken place in a wide variety of geographical contexts, with information shared across political boarders, often with some degree of potential intellectual property violation. These conditions are exacerbated by the COVID-19 pandemic, and as such, the

information practices of biomedical repair technicians are a more than suitable candidate for forensic investigation.

The forensic and metadata features selected for analysis have been identified in a series of steps designed to quantify and interpret meaningful features among a corpus of textual objects (Dalbello-Lovric, 1999; Hodges, 2019). As practiced in this study, there are four general steps in this process: retrieval of sources, classification according to apparent properties (without looking at content), identification of patterns that emerge during classification, and historical inference in order to contextualize findings. Retrieval began with identifying a corpus of documents specifically related to the role of medical technicians during crisis, in order to see the ways an emerging information order brings to light new perspectives on the documents that they employ. Classification began by reviewing the document contents for evidence of reader behavior such as annotation or editing. These alterations, largely taking the form of handwritten notes akin to the marginalia studied by book historians (Jackson, 2001; Sherman, 2010), are understood as evidence for the layered temporal path that documents take through successive print and digital instantiations. Next, the study classifies objects according to specifically digital characteristics like file format and metadata. After this step, the study notes evidence of documents' variety in terms of temporal origin and revision history, including documents that were scanned with handwritten notes and files using early versions of PDF later ported forward into newer versions. Categories of alteration were noted and classified iteratively until categories achieved saturation, in a process informed by grounded theory and theoretical sampling (Corbin & Strauss, 2015; Yingling & McClain, 2015). Finally, historical inference was achieved by reviewing the history of the PDF format itself, via technical documentation such as Adobe's official specifications (Adobe Systems, Inc., n.d.), as well as secondary technical publications (Ball, 2007), in order to understand the timeframe for different versions of the format and the associated metadata formats for each. A list of documents and findings is provided in Table A1.
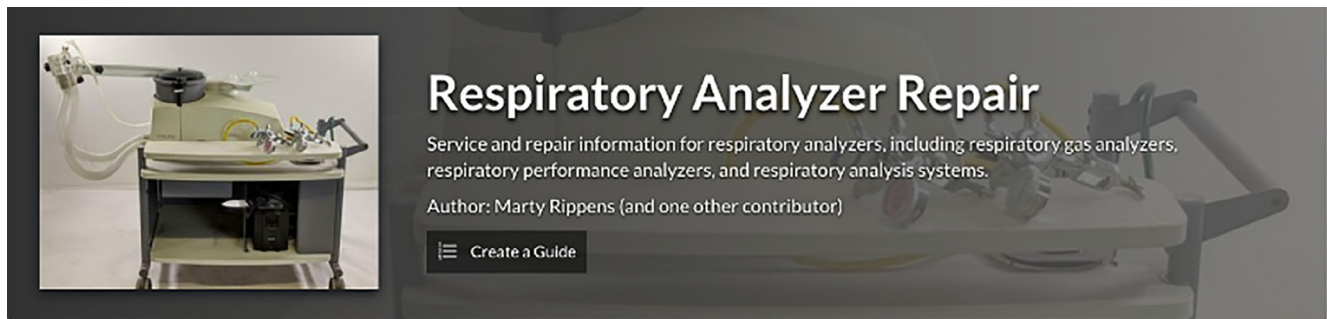
The decision to focus on the metadata and format-related features of documents is informed by the methodology of trace ethnography. Trace ethnography aims to examine documents as a way of understanding "actors and events that are often invisible in today's distributed, networked environments" (Geiger & Ribes, 2011, p. 1). A forensic approach to document research is closely related to trace ethnography, because it capitalizes on the traces left behind in digital systems that log "specific actions taken by uniquely-identifiable individuals with very fine levels of granularity" (Geiger & Ribes, 2011, p. 1). Where this study differs from traditional trace ethnography,

however, is in its lingering at the more diffuse scale of aggregate activity among a professional community, rather than deep engagement with traces generated by individual workers. In this sense, the present study builds equally on work by scholars like Finn, Srinivasan, and Veeraraghavan, who use documents to understand social relations at the level of interaction between state agencies and entire populations (Finn et al., 2014, pp. 1516–1517). By charting a middle course, between highly localized individual practices and population-level state relations, this study advances a meso-scale analysis of professional information workers operating in a medical context.

In a distributed geographical context, such as online crowdsourcing among biomedical repair technicians, textual documents and interactions are one of the primary ways that knowledge can be shared. As Marsh (2016) has argued, documents used in institutional contexts frequently work as records not only of the information recorded therein, but also of "relations among persons, material culture, and other affective encounters" when read in context (Marsh, 2016, p. 126). One key difference exists, however, between the present study and more traditional approaches to trace ethnography. Scholars like Marsh, as well as Geiger and Ribes, generally conduct studies focused on systems in which users' traces are extensive and institutionally generated; the present study instead focuses on a more heterogeneously distributed setting, where varied professional behaviors and resources in different social and geographical contexts make the generation of traces potentially inconsistent. This divergence is in part related to the event epistemology of COVID-19, which has occasioned contact between geographic and professional groups that do not normally interact, each with their own idiosyncratic information systems and practices. Thus while the traces inscribed on repair manuals generally predate COVID-19, the ability to compare them in a single corpus has been enabled by epistemological changes prompted by the pandemic.

3 | FINDINGS

In the top-level directory for Respiratory Analyzers, a series of 11 subfolders contains 40 PDF files documenting the operation and maintenance of devices crucial to monitoring patients' lung function when hospitalized with respiratory issues such as those often associated with -COVID-19 (Respiratory Analyzer Repair, n.d.). By examining the metadata in each file to reconstruct the personal information practices of biomed technicians, this study also develops a conceptual model of layered temporality that has been enabled by the emergent epistemic changes produced during a global medical
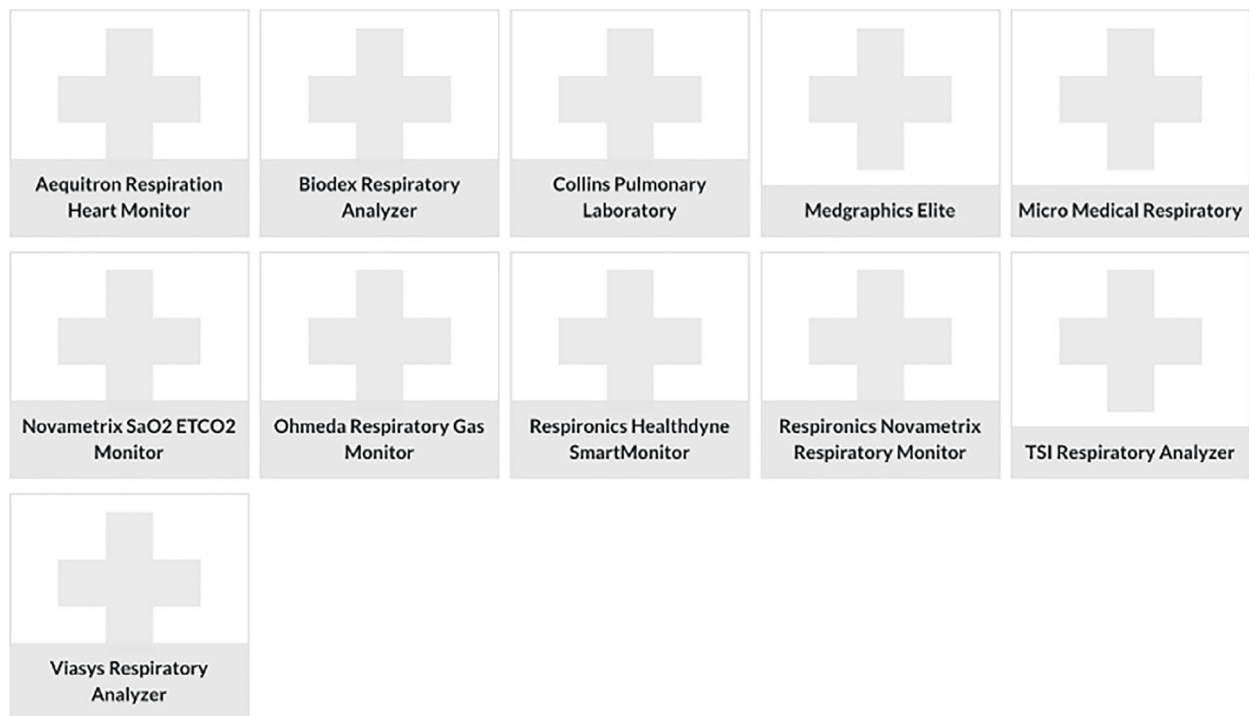
FIGURE 1   Top-level directory of iFixit's Respiratory Analyzer file collection, as seen using iFixit's web-based file browser

emergency. Overall, the documents reflect a wide variety of computational operating contexts.

3.1 | Novametrix Model 7000: A key example of findings

One particularly rich example from this study's findings can exemplify both the types of traces left behind during work with a document (RQ1), and the complex, changing epistemological conditions inherent in both biomedical technicians' professional activities and the documents that they collect in the course of such work (RQ2). The iFixit collection contains an instruction manual, in PDF format, for the Novametrix 7000 respiratory analyzer with its front page listing a publication date of July 20, 1989 (Novametrix Model 7000 Repair, n.d.). The second scanned page of the Novametrix Model 7000 manual contains a list of handwritten notes enumerating maintenance costs and part numbers, showing that the

manual is a living document of sorts, with marginalia used to enhance its usefulness in situ (see Figures 2 and 3). These handwritten notes are also an example of the multi-layered temporality that is pervasive within iFixit's collection. In the course of biomedical repair technicians' careers, they frequently collect and work on objects from a variety of times and places. The event epistemology that emerges is one characterized by increased awareness of

disparities between rich and poor hospitals, old and new equipment, and technicians with larger or smaller collections of documents. As a result, any attempt at meeting the information needs of this population has to take into account its heterogeneity.

An analysis of the document's XMP metadata provides additional detail on the multi-layered temporality of the Novametrix 7000 instruction manual (see Figure 4). For
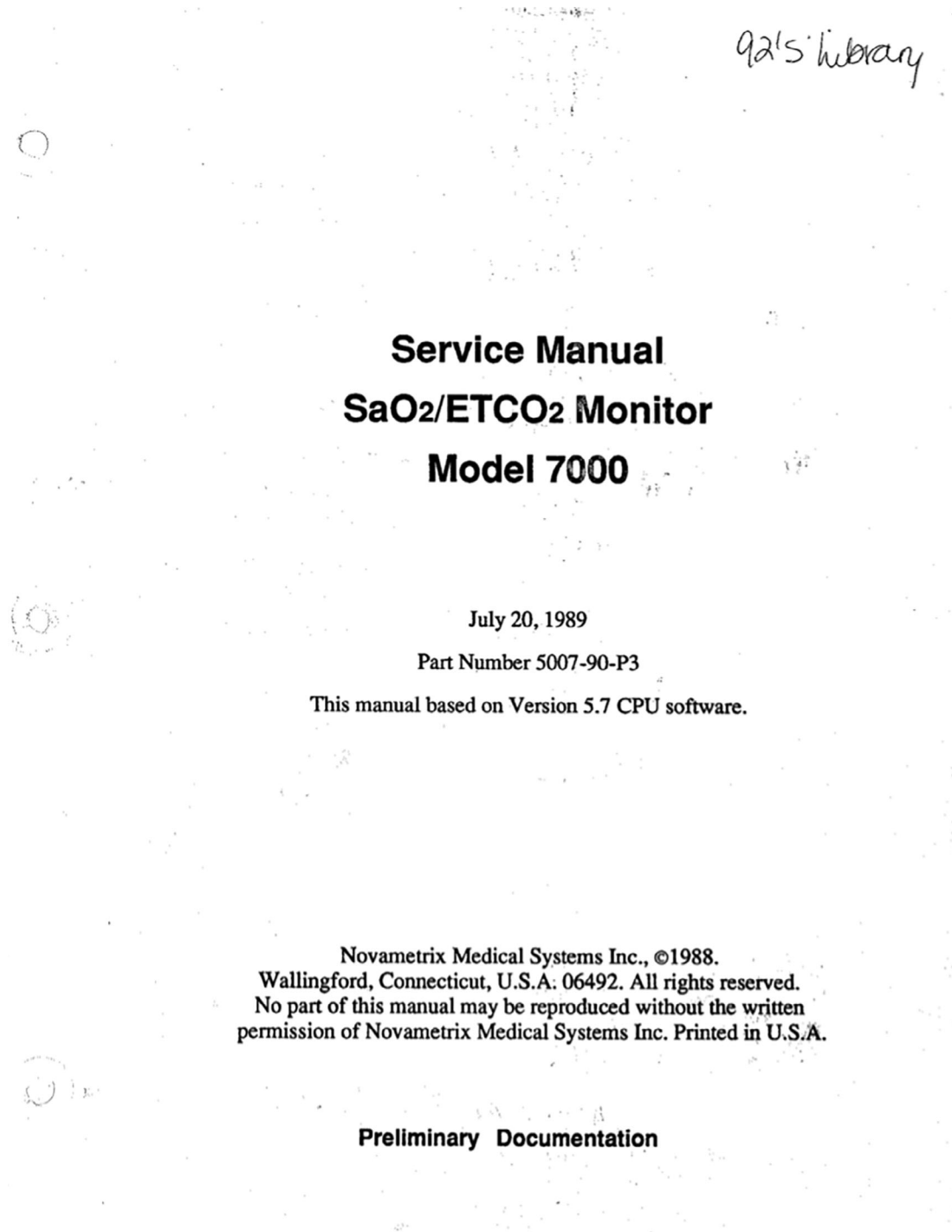

FIGURE 2 Page 1 of the Novametrix Model 7000 Service Manual

FIGURE 3 Page 2 of the Novametrix Model 7000 Service Manual

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<pdf:Producer>pikepdf 1.10.2</pdf:Producer>
<xmp:ModifyDate>2020-04-20T01:46:34+00:00</xmp:ModifyDate>
<xmp:CreateDate>2020-04-20T01:46:11Z</xmp:CreateDate>
<xmp:CreatorTool>ocrmypdf 9.7.1.post7+g58abb57.d20200415 / Tesseract OCR-PDF 4.1.0</xmp:CreatorTool>
<xmp:MetadataDate>2020-04-20T01:46:34.942754</xmp:MetadataDate>
<xmpMM:DocumentID>uuid:42e8293f-bac5-11f5-0000-5d34a4e2d9c3</xmpMM:DocumentID>
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FIGURE 4 XMP metadata from the Novametrix Model 7000 Service Manual. Note the presence of "pikepdf" and "Tesseract" in the "Producer" and "CreatorTool" fields, respectively

example, despite its purported publication date in 1989, this digital file was actually generated in 2020 using version 1.7 of the PDF standard (initially introduced in 2018). Metadata also show that the file was created using contemporary command line tools called PikePDF and Tesseract. Usage of command line tools demonstrates a degree of technical proficiency in the production and circulation of this particular document, which may correspond with the technical skill and attention to detail at evidence in the file's use of XMP metadata in the first place. In contrast, many other documents from the collection were produced using programs such as Apple Preview, the stock PDF viewer packaged with Macintosh operating systems. Far more of the files do not include XMP data at all. This finding reveals another layer of temporal composition, with a single object showing multiple stages of intervention. Overall, the findings show this particular document, like many technological and print resources related to biomedical repair and maintenance, to have a long and varied lifecycle.

3.2 | RQ1: Traces of professional activity recorded in PDFs

While an analysis of document features *can* provide meaningful insight regarding the tools and techniques used to circulate knowledge about biomedical repair, many available tools and standards for providing additional information about document features are not widely utilized. Only three of the 40 files (7.5%) make use of the XMP (Extensible Metadata Platform) format supported by PDF since version 1.4 was released in 2001, despite the fact that 22 of the 40 files (55%) are encoded in versions of the PDF standard that could support this feature (Adobe Systems, Inc., n.d.). The files containing XMP information convey information about author's names and the software tools used to encode file data, but the overall lack of usage shows that existing metadata models are not widely used by practicing technicians. Therefore, the study finds that future research should assess the reasons for infrequent XMP adoption, as well as potential value (or pitfalls) inherent to supporting more metadata generation among technicians. Along similar lines, only 2 files (5%) comply with PDF/A standards, which are designed to facilitate long-term preservation of documents. This finding suggests that despite the fact that technicians frequently work with aging machines and documentation, long-terms storage is not prioritized. As a result, information professionals may identify long-term stability and storage as a priority area where there is great potential to assist in biomedical repair and maintenance labor.

3.3 | RQ2: Changing documents and epistemic conditions

Overall, files range from PDF version 1.2 (current from 1996 to 2000) to 1.7 (2006–present). PDF standards 1.2 and 1.3 are used for nine documents each, totaling 18 documents or 45% of documents. Version 1.4 (2001–2003) accounts for an additional two documents, meaning that the half of the documents use PDF standards that have been discontinued for well over a decade. One in four files uses a version of PDF that is separated from the stated date of publication by more than a decade. Eight files (20%) show evidence of being digitized or ported to new formats at some point years after their initial publication. In a computing and biomedical field that is constantly subject to changing technological conditions, this finding suggests that biomedical repair technicians operating within global contexts are still collecting and trading documentation for old devices, using old computer hardware and software. Thus the temporal components of biomedical repair and maintenance should be understood to be unevenly distributed, with documents, files, and operating environments often presenting a combination of new and old technologies. The epistemic conditions created by COVID-19 highlight longer-standing and more general characteristics of technical labor, which is characterized by documents and information environments that change over time and are unevenly distributed through space.

Initial publication dates run back even further than PDF standards, to 1989. In other words, the documents circulated among technicians predate the technological regime within which they are currently operating. Seven of the 40 files contain handwritten annotations (17.5% of files). Two of these annotated files contain handwritten page numbers, added to provide continuous page numbering despite the addition of new pages and attachments after initial publication. Five of these files contain circling, underlining, and other forms of marginalia. In other words, documents are not static in their structure or contents. Technicians can add or remove contents to a document over the course of working with it in order to ensure that contents are up-to-date or optimally organized. In other cases, documents that have been circulated in a print version may simply have come apart or had pages separated during the wear-and-tear of everyday use. These findings serve as a reminder that technological systems are not developed and adopted instantaneously, or even along a linear timeline. Instead, change over time progresses unevenly, linking pre-digital publications and annotations with contemporary software and file formats.

In other cases, variation between files is not readily apparent to the unassisted human viewer. The collection

contains two sets of apparent duplicate files, but only one of the duplicate pairs is truly identical from a computational perspective. This finding shows that the same physical document—or very nearly identical physical documents—have been scanned and circulated along separate paths through time and space. While the unaided observer would note that iFixit's "Micro-Medical-MicroLab-ML3500-Service-manual" (m24) and "Micro_Medical_MicroLab_ML3500_-_Service_manual" (m19) files appear to differ only in their use of dashes versus underscores in the filename, a computational comparison using the SHA-1 cryptographic hash function shows that the files are subtly distinct beyond the filename, which does not affect hashing (Micro Medical Respiratory Repair, n.d.).[1] The "Aequitron Respiration Heart Monitor Model 9500 9550 Technical Manual" (m1) and "Aequitron-Respiration-Heart-Monitor-Model-9500-9550-Technical-Manual" (m2), on the other hand, generate identical SHA-1 checksums (Aequitron Respiration Heart Monitor Repair, 2020).[2] In yet another case of nearly identical files, the "Biodex Pulmonex II Operator Manual" (m6) and "Biodex Pulmonex II Operation Manual (1)" (m5) possess highly similar contents and filenames, yet are encoded using different versions of the PDF standard (1.6 and 1.5, respectively). Once again, highly similar files have been circulated through distinct paths between initial production and their current state.

File names and document titles can also accumulate inconsistencies over the course of their life cycle. Six of 40 files contain such characteristics (15% of total files). Some of these errors are attributable to a human mistake during digitization or processing. For example, the "Collins-Eaglet-Pulomnary-Diagnostic-Spirometer-Instruction-Manual" misspells "pulmonary" as "pulomnary" (m12) (Collins Pulmonary Laboratory Repair, n.d.). The "Medgraphics Elite plethysmograph Trouble Shooting Guide (1)" (m18) file shows evidence of a different inconsistency, this time related to "(1)" tag at the end of the file name, presumably due to presence of another identically titled file on some technician's hard drive (Medgraphics Elite Repair, n.d.). This file also contains errors in pagination. Other inconsistencies related to numbering can be seen in the form of the "Ohmeda 5250 Respiratory Gas Monitor Service Manual – Part 1" (m33), a document for which there is no "Part 2" (Ohmeda Respiratory Gas Monitor Repair, n.d.).

Finally, additional inconsistencies can be noted in the form of branding and manufacturer attributions, reflecting the constantly changing nature of commercial manufacturing and healthcare industries. For example, the Respironics company acquired competitors Healthdyne Technologies and Novametrix around the turn of the 21st century, which leads to potential confusion when consulting documents labeled alternately as both "Novametrix" and "Respironics Novametrix" (m29; m38) or "Healthdyne" and "Respironics Healthdyne," depending on the year of publication (m16; m17; m36; m37) (Respironics Healthdyne SmartMonitor Repair, n.d.). These changes are a window into some of the problems facing biomedical technicians, as official responsibility for providing documentation is shuffled between manufacturers, with potential for lapses or interruptions in support.

On the topic of change over time, four of the 40 files (10%) bear some form of marking that designates them as revised editions, reminding observers that in addition to changes in document structures and features as the result of user alteration, as well as changing corporate ownership and branding, documents can be altered by publishers as well. Thus an analysis of the iFixit respiratory analyzer files provides an overview of the changing conditions inherent to biomedical device repair and maintenance. Files are constantly changing, whether the result of user alteration, corporate restructuring, or updated knowledge. These conditions appear to predate COVID-19, but the pandemic created new epistemological circumstances that further highlight and emphasize the uneven and nonlinear nature of documents' temporality.

4 | CONCLUSION

Based on the findings, the study proposes a model of layered temporality that includes four steps where interventions change document forms and contents. Multiple copies of the same document can diverge at any point in the lifecycle, leading in some cases to multiple copies of the same document possessing meaningful differences in terms of additional information relevant to technicians operating within different geographic, economic, linguistic, and temporal circumstances. These steps of intervention are initial publication, print annotations, digitization, and porting forward.

Based on evidence that documents have been altered at each step of this lifecycle, observers may surmise that documents accrue additional meaning over time, and therefore that limiting emergency archival resources to the collecting of a single authoritative edition would prevent technicians from sharing potentially valuable knowledge. In other words, the preservation of multiple subtly different documents may assist in collecting meaningful additions that the documents have gathered over time. While browsing multiple copies of a document can present an unwanted drain on technicians' time, increased support for quick browsing and comparison can help to mitigate this problem.

At the same time, each step where intervention is possible also has the potential to act as an opportunity for misinformation, even if it is accidental. For example, a technician looking for up-to-date documentation of a particular device may be misled by the PDF file's creation date or the document's apparent date of publication, leading to a waste of valuable time, or even an incorrect maintenance procedure. Some files also contain personal information left behind by a user who digitized or modified the file, potentially implicating them in violating intellectual property restrictions. The complex temporality of technical documentation should inform design and deployment of information systems for emergency and professional usage that more clearly guide professionals in the selection and deployment of accurate, meaningful, and timely documentation.

Overall, the event epistemology triggered by COVID-19 is characterized by new awareness of the need to share resources across facilities and geographic locations. The pandemic has created new conditions under which knowledge is shared and produced, defined in part by sharing of resources. An analysis of these shared resources, in turn, shows how uneven the distribution of expertise and resources can be. Knowledge and documents both follow non-linear paths, with older documents assuming new file formats and accruing new annotations. The information community has resources and expertise that can assist in supporting the collection, processing, and comparison of documents that often appear similar, yet actually contain meaningful alterations and variations. Long-term storage presents another area with potential for improvement, as many documents appear to enjoy long life cycles, yet receive little in the way of long-term stability of the sort afforded by formats like PDF/A.

While many of this study's findings relate directly to the working behaviors of biomedical technicians, the study presents broader implications for academic research as well. This study shows that interactions between labor and technology are frequently mediated by documents. Crisis informatics research has already identified the key role of information technologies in mediating the experience of and response to natural disasters (Finn et al., 2014), but the present study further emphasizes the role of print documentation in the maintenance of technical infrastructure itself. Thus, while Julian Orr's workplace ethnography hones in on the negotiation between "customers and machines" (Orr, 1996, p. 3), this study shows that technicians also negotiate with documents. Pagination is reordered, contents are added or removed, and file formats are changed over time. Information sharing has taken on increased significance due to pandemic-related epistemic shifts. Trace records of biomedical repair technicians" information practices have

become more accessible, highlighting the significance—and the changing nature—of technical documentation and digitized documents.

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ENDNOTES

[1] The SHA-1 checksums are a553298d4c12b537e97fd68757 0ef33859b7cacf and 66c50e63ed5a386bfb06816e46075cafe81ad474, respectively.

[2] The SHA-1 checksum is c540b810ac7a2d71b80a63dc86daaa0 8b7b0a253.

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APPENDIX

TABLE A1   List of respiratory analyzers, with document number, file name, manufacturer, document title, print annotations and PDF version.

Document number	File name	Manufacturer	Document title	Print annotations	PDF version
m1	Aequitron Respiration Heart Monitor Model 9500 9550 Technical Manual	Aequitron Medical Inc	Technical Manual	Yes	1.7
m2	Aequitron-Respiration-Heart-Monitor-Model-9500-9550-Technical-Manual	Aequitron Medical Inc	Technical Manual	Yes	1.7
m3	Biodex Pulmonex II Double-Trap Xenon Operator Manual	Biodex	Operation Manual	No	1.4
m4	Biodex Pulmonex II Hose Replacement Guide	Biodex	"How to Replace All Hoses"	No	1.7
m5	Biodex Pulmonex II Operation Manual (1)	Biodex	Operation Manual	No	1.5
m6	Biodex Pulmonex II Operator Manual	Biodex	Operation Manual	No	1.6
m7	Biodex Pulmonex II Xenon Operator Manual	Biodex	Operation Manual	No	1.3
m8	Biodex Pulmonex Leak Test Procedure	Biodex	Leak Test Procedure for the Pulmonex	No	1.7
m9	Collins-BPD-Body-Plethysmograph-System-Instruction-Manual	Collins Medical	Instruct-ion Manual	No	1.3
m10	Collins-CPL-CPLPF-Instruction-Manual	Collins Medical	Instruction Manual	No	1.3
m11	Collins-Eagle-Instruction-Manual	Collins Medical	Instruction Manual	No	1.3
m12	Collins-Eaglet-Pulomnary-Diagnostic-Spirometer-Instruction-Manual	Collins Medical	Instruction Manual	No	1.3
m13	Collins-GEM-Owl-Hawk-Eagle-Instruction-Manual-Addendum	Collins Medical	User's Manual Addendum	No	1.3
m14	Collins-Owl-Hawk-Instruction-Manual	Collins Medical	Instruction Manual	No	1.3
m15	Collins-Plus-2000-System-Instruction-Manual	Collins Medical	Instruction Manual	No	1.3
m16	Healthdyne SmartMonitor Service Manual	Healthdyne	Professional Manual	No	1.7
m17	Healthdyne SmartMonitors Procedure Manual	Healthdyne	Checkout Procedure Manual	No	1.7
m18	Medgraphics Elite plethysmo-graph Trouble Shooting Guide (1)	Medgraphics	Trouble-shooting Guide	Yes	1.7
m19	Micro_Medical_MicroLab_ML3500_-_Service_manual	Micro Medical	Service Manual	No	1.2
m20	Micro-Medical-CO-Meter-Service-Manual (1)	Micro Medical	Service Manual	No	1.5
m21	Micro-Medical-Micro-CO-Meter-Service-Manual (1)	Micro Medical	Service Manual	No	1.2
m22	Micro-Medical-Micro-H2-Meter-Service-manual	Micro Medical	Service Manual	No	1.2
m23	Micro-Medical-Micro-MicroPlus-Service-manual	Micro Medical	Service Manual	No	1.2
m24		Micro Medical	Service Manual	No	1.2

(Continues)

TABLE A1 (Continued)

Document number m1	File name Aequitron Respiration Heart Monitor Model 9500 9550 Technical Manual	Manufacturer Aequitron Medical Inc	Document title Technical Manual	Print annotations Yes	PDF version 1.7
	Micro-Medical-MicroLab-ML3500-Service-manual				
m25	Micro-Medical-MicroLoop-Service-manual	Micro Medical	Service Manual	No	1.2
m26	Micro-Medical-MicroRint-Service-manual	Micro Medical	Service Manual	No	1.2
m27	Micro-Medical-Mouth-Pressure-Meter-Service-manual	Micro Medical	Service Manual	No	1.2
m28	Micro-Medical-Smoke-Check-Service-manual	Micro Medical	Service Manual	No	1.2
m29	Novametrix Model 7000 Service Manual Part 1 (1)	Novametrix	Service Manual	Yes	1.7
m30	Novametrix Model 7000 Service Manual Part 2 (1)	Novametrix	n/a	Yes	1.7
m31	Ohmeda 5120 Operation And Maintenance Manual	Ohmeda	Operation and Maintenance Manual	Yes	1.7
m32	Ohmeda 5120 Service Manual	Ohmeda	Service Manual	Yes	1.7
m33	Ohmeda 5250 Respiratory Gas Monitor Service Manual – Part 1	Ohmeda	Service Manual	No	1.7
m34	Ohmeda_Respiratory_Gas_Monitor_5,250_-_Service_manual	Ohmeda	Operation and Maintenance Manual	No	1.7
m35	PortaCount-Pro-Manual	TSI Incorporated	Operation and Service Manual	No	1.6
m36	Respironics Healthdyne SmartMonitor 900S 900SL 950S 970S 1B 1C Manual	Healthdyne	Professional Manual	No	1.7
m37	Respironics Healthdyne SmartMonitor Models (Several) Home & Hospital Checkout Procedure Manual	Healthdyne	Checkout Procedure Manual	No	1.7
m38	Respironics Novametrix 8100 Service manual	Novametrix	Service Manual	No	1.3
m39	Viasys-Vmax-Encore-Technical-Reference-Manual	Viasys	Technical Reference Manual	No	1.5
m40	Viasys-VMax-SpectraOp-operators-manual	SensorMedics (a division of Viasys Healthcare)	Operator's Manual	No	1.4